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Life Cycle Analysis of Lab-Scale Constructed Wetlands for the Treatment of Industrial Wastewater and Landfill Leachate from Municipal Solid Waste: A Comparative Assessment

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Abstract: Purpose: The objective of this study was to measure the environmental impact of five different laboratory-scale constructed wetland (CW) treatment systems with varying design approaches, which have been employed to treat different types of wastewater. Moreover, the present study also assessed the feasibility of treating landfill leachate using four different hybrid wetlands built outdoors, and analyzed the environmental viability based on the life cycle assessment (LCA). Primarily, the choice of media materials has been the focus of evaluating the sustainability of the systems, as for each system the media materials cover major material consumption and define treatment performance. Methods: This study applied a life cycle assessment using the SimaPro software tool to quantify the environmental impacts from the constructed wetland systems. Primarily, the LCA has been applied by adopting the ReCiPe 2016 method with cross-validation using the Impact 2002+ method. Moreover, an uncertainty analysis has been performed to determine any uncertainties involved in the datasets, along with sensitivity analysis on the inventory. Results and discussions: As the results suggest, the systems employed for wastewater treatment using cement mortar have the highest environmental burden. In contrast, the natural media choices, sugarcane bagasse and coco-peat, have proved to be environmentally favorable. Media employment from recycled materials like brick and steel slag could significantly redeem the previous environmental burdens of these materials, providing treatment efficiency. However, the systems employed for landfill leachate treatment revealed the CW using brick chips as the most vulnerable system with regards to environmental concerns, implying that the media brick chips are certainly the major contributor behind this high leap in the scale. However, both the systems worked very well in the carcinogenic category, providing good treatment performance, and eventually exerting lesser impact. Conclusion: The overall assessments suggested choice of media materials are essential to deciding the sustainability of a CW design. However, the CW is more beneficial and environmentally friendly than the other treatment methods, until the design scale has a high capacity. Nevertheless, the choice of the LCA method is also significant, while measuring impact scales.

Keywords: life cycle assessment; wastewater; landfill leachate; constructed wetlands; treatment; Impact 2002+; ReCiPe 2016; municipal; industrial

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1. Introduction

As the world is progressing towards sustainable solutions to pollution and waste management while considering technological feasibility, natural wetlands have established their importance as treatment solutions with reduced footprints. The most important attribute of this green technology is the production of acceptable effluent quality without renewable energy input and minimum operational requirements [1]. In a constructed wetland (CW) system, wastewater flows through an integrated network of plant roots, media, and attached biofilm, where pollutant removals (i.e., organics, nitrogen, phosphorus, solids, metals, and coliform) are mostly favored [2,3]. Despite being a cheaper and environmentally friendly way to carry out effluent treatment compared to mechanical techniques, the sustainable performance of CWs is still a challenge due to the different types of media and plants used for treatment purposes, along with other operating parameters [4]. Therefore, effective wetland design should consider the environmental friendliness of the media categories as a decisive factor, in addition to effective treatment performance.

With a view to achieving an understanding of the impacts that wetlands might exert on the environment, life cycle assessment has been considered one of the most intensively used tools for assessing the environmental impacts of products and production processes across their lifespan [5]. LCA is a systematic, comprehensive, and standardized process for assessing the potential environmental impacts of a product, practice, or activity using a cradle-to-grave approach [6]. LCA is usually used for choosing amongst technologies, products, or services with similar performance, through accounting for the impacts caused by each alternative over its life cycle. It can also be applied to identify which of the life stages brings the most significant environmental impacts and establish baselines for further research improvement.

A number of studies have employed LCA on CWs with specific objectives to understand the environmental burdens of CW treatment technologies, assessing the environmental impact of CW technology combined with other treatment technologies [1,7], carrying out a comparative impact assessment between CW and other treatment options [8–10], and assessing the impacts from CW systems devoted to different sources of wastewater [11,12]. The choice of life cycles for the abovementioned studies have been considered widely with modifications of the systems and treatment goals; nevertheless, common considerations included the consumption of construction materials to build the systems, the electricity consumption of the treatment operations, and the emission of effluent back into the environment. However, some studies also took into account the gaseous emissions from the treatment systems and the fate of the residue from the processes. Through continuous evaluation and reports on previous research works, the CW has been proven to exert the most negligible environmental impact in comparison with many established treatment techniques [11,13]. The differences are primarily attributed to the least electricity usage and chemical consumption by CW treatment techniques [8]. Nevertheless, given the widely used design approaches and media utilization on the basis of treatment objectives, previous studies could not be conclusive on the environmental impact of CW treatment technologies. Moreover, the impact of the utilization of media materials has not been extensively investigated previously. Comparative impact assessment, among different CW treatment configurations, remains limited as well.

While previous studies of LCA have primarily focused on full-scale CW treatment technologies, this study is a new inquiry that draws a representation of the environmental impacts from lab-scale CWs, considering the different treatment configurations and media utilization. Therefore, this study aims to accomplish a comprehensive comparative assessment (through LCA) of the environmental burden that various configurations of laboratory-scale constructed wetlands might exert, in contrast with their pollutant removal performance from wastewater and landfill leachate prior to environmental discharge.

2. Materials and Methods

2.1. Description of CW Systems for the Treatment of Industrial Wastewater

In total, five different small-scale, constructed wetland systems have been considered for LCA application to industrial wastewater treatment. These hybrid wetlands are the result of prior research conducted in Bangladesh, where laboratory-scale constructed wetlands (CWs) were studied for their treatment efficiencies with different types of wastewater sources. Table 1 summarizes the characteristics of the five selected constructed wetland systems. The details presented in the table are based on relevant previously published articles (the respective references are provided in the table). In addition, schematic configurations have been included for all the systems in the Supplementary Information file (Figures S1–S4) for reference.

Table 1. Constructed wetland system characteristics and influent/effluent characterization.

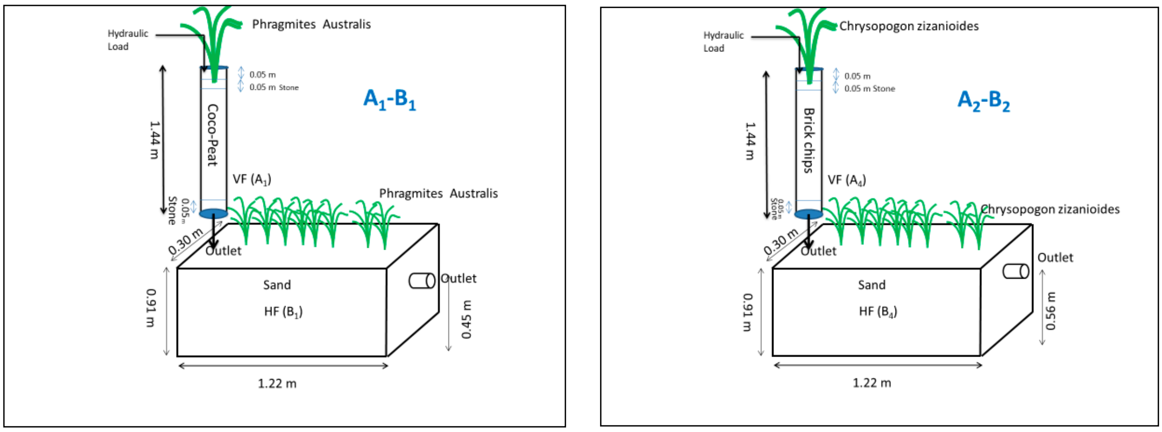
	Unit	S1	S2	S3	S4	S5
System Characteristics						
Flow rate	L d^{-1}	38	4	4	4	6
Plants used		*Phragmites australis*	*Phragmites australis*	*Canna indica*	*Canna indica*	*Phragmites australis*
Hydraulic retention time	D	12.5	32.8	27.9	27.9	28.3
No. of vertical CW cells		2	2	1	1	1
vertical cell dimensions	m (H × D)	0.73 × 0.91	1.5 × 0.15	1.53 × 0.15	1.53 × 0.15	2.13 × 0.15
No. of horizontal CW cells		1	1	1	1	1
horizontal cell dimensions	m (H × L × W)	0.78 × 1.32 × 1.01	0.5 × 1.22 × 0.61	0.92 × 0.90 × 0.30	0.92 × 0.90 × 0.30	0.91 × 1.22 × 0.61
Influent quality						
BOD_5	mg/L	4200 (43.5)	131.5 (3.4)	215 (6.1)	215 (5.5)	96.4 (4.5)
COD	mg/L	11500 (410.2)	420.3 (13.3)	1098 (32.5)	1098 (21.4)	171.5 (10.5)
TN	mg/L	100.3 (5.4)	31.3 (1.9)	17.3 (1.5)	17.3 (1.4)	59.3 (3.5)
TP	mg/L	30 (2.1)	2.3 (0.2)	4.6 (0.12)	4.6 (0.2)	14.1 (0.4)
Effluent quality						
BOD_5	mg/L	80 (3.5)	8.8 (1.5)	28.4 (3.5)	56.2 (4.8)	3.7 (0.5)
COD	mg/L	200 (5.1)	45.2 (3.9)	184 (4.2)	362.9 (8.2)	22.2 (1.5)
TN	mg/L	49.8 (5.2)	3.1 (0.15)	3.4 (0.2)	5.6 (0.3)	2.4 (0.2)
TP	mg/L	3 (0.25)	0	0.5 (0.05)	1.6 (0.01)	0.5 (0.01)
Reference		[14]	[15]	[16]	[16]	[17]

Note(s): Standard deviations are presented in parenthesis.

The wetland system S1 treated tannery wastewater, employing a three-stage hybrid system: a vertical flow (VF) unit followed by a horizontal flow (HF) unit, and another VF wetland as the last stage (Supplementary Figure S1). Coco-peat, cupola slag, and gravel were used as the main media in the first, second, and third-stage wetland units, respectively. The S2 system also consisted of three consecutive treatment units (Supplementary Figure S2); the first two were VF units, followed by a subsurface stage using mortar, recycled brick, gravel, and sand as media materials. Wetland systems S3 and S4 treated industrial wastewater, consisting of one VF and one HF treatment stage using recycled brick and sugarcane bagasse as media materials, respectively (Supplementary Figures S3 and S4). Concomitantly, S5 also employed a VF unit followed by a HF unit, and the media materials employed for the VF were biochar, while the HF used sand and cement mortar in combination (Supplementary Figure S4). According to the design objectives, S1 was devoted to the treatment of wastewater from tannery industries. In contrast, other types of industrial wastewater fed the systems S2, S3 and S4, while S5 was employed for nutrient removal from municipal sewage. In terms of flow rate, the S1 system had the highest treatment capacity of 38 Ld^{-1}, while the other systems ranged between 4–6 Ld^{-1}. These systems were mainly established to determine the treatment efficiencies of different wetland designs combining different media materials. A more detailed description of these systems with treatment insights is available in the respective publications [14,18].

2.2. Description of CW Systems for Landfill Leachate from Municipal Solid Waste

Four different hybrid wetlands systems, i.e., VF and HF wetlands, were used and built outdoors at the University of Asia Pacific, Bangladesh. The VF wetlands were made of PVC pipes. The height and diameter of each PVC pipe was 1.5 and 0.15 m, respectively. The HF wetlands were made of steel sheets. Each SF unit's length, width, and height were 1.22, 0.61, and 0.5 m, respectively. Experimental wetland units were arranged to form two parallel system trains, and each system included one VF unit as the first (A), followed by a second HF unit. Figure S4 provides the wetland dimensions and arrangements, along with the employed media. Figure 1a,b illustrate the engineered drawing of the experimental set-up for heavy metal treatment.



(**a**) (**b**)

Figure 1. (**a**,**b**). Engineered drawing of experimental set-up: (**a**) A_1-B_1; (**b**) A_2-B_2, for heavy metal treatment.

The VF wetlands of system A_1-B_1 are packed with biological material coco-peat; the VF units of system 2 included construction material brick chips. Each VF unit has maintained a media depth of 1.36 m in each unit. Large stones have been provided on the top and bottom of each VF wetland unit to facilitate influent distribution and effluent discharge, respectively. In the HF wetlands, sand material has been used to support plant growth; the depth of the sand bed is 0.15 m in each unit (Figure 1). System A1-B1 has been planted with Phragmites australis, and A_2-B_2 with Chrysopogon zizanioides. After plantation, these units were waterlogged for ten weeks to allow plant growth and maturation. The wastewater dosing in each wetland system was applied as input into the VF unit 5 days a week with a feeding rate of 334 mm/day for 10 weeks. After the first 5 weeks, 50% of the effluent had been re-circulated into each system.

2.3. Life Cycle Assessment

The present research has been carried out, according to the ISO standard [6], to assess the environmental impact of CW treatment systems through LCA application, where it has been recommended that the LCA needs to be conducted in four different phases: goal and scope definition, inventory analysis, impact assessment, and interpretation of the results. Hence, the application of the LCA in this study has been carried out according to the following different phases, and the following sections briefly elaborate on the specifics of each of the phases.

2.4. Goal and Scope Definition

The present study aimed to evaluate the potential environmental impacts associated with CW treatment systems for different wastewater and landfill leachate sources. More specifically, the role of different media materials under different design set-ups of laboratory-scale CWs were inspected to determine the most sustainable option for large-scale applications. Since the significance of any treatment system is based on the amount of wastewater and landfill leachate treatment provided in the design period, the functional unit has been defined as 1 m^3 of wastewater treated for LCA application. The system boundaries primarily included the construction and operation stage in the design life cycle of each treatment system.

The media materials have been considered independently without associating them specifically with the construction phase and were focused on understanding the impact scales. The electricity consumption mostly occurred during treatment operation to operate the water pump to feed the treatment units. Since the major environmental concern of a wastewater treatment unit is the discharge of treated water into the environment, it has been taken into account in the system boundaries. The system boundaries did not consider the ultimate fate of the structures and the maintenance equipment at the end of the study, due to their minimal contribution compared to the overall materials involved [11]. Additionally, the transportation of materials has not been considered since mostly local products were utilized in the CW systems [14]. Moreover, unlike conventional treatment systems, a CW does not have any sludge accumulation in the media materials to require a sludge treatment phase, and thus was exempted from this study [9].

2.5. Inventory Analysis

The inventory data of all the hybrid constructed wetland systems from the life cycle phases under consideration are summarized in Table 2. The consumption of materials involved in each of the systems mainly derived from constructing the wetland systems and the requirement of a media for water treatment. The estimation for the inventory has been made for a functional unit of 1 m^3 of water with ten years' design life, considering the media materials are being renewed each year within the design scale [7]. The LCA modeling was supported by data from the ecoinvent database V3.4, which is widely recognized as one of the best resources for life cycle inventory information [19].

Table 2. Inventory results referred to m^3 of wastewater treatment for considered constructed wetland systems.

		CW Systems				
	Unit	**S1**	**S2**	**S3**	**S4**	**S5**
Construction materials						
PVC	kg/m^3	0.125	1.562	1.195	1.197	0.757
Steel	kg/m^3	–	3.59	3.51	3.51	3.63
Media materials						
Coco-peat	kg/m^3	0.274	–	–	–	–
Scraped metals	kg/m^3	38.06	–	–	–	–
Local gravel	kg/m^3	31.23	8	–	–	–
Cement mortar	kg/m^3	–	8.88	–	–	232.48
Brick	kg/m^3	–	5.92	154.15	–	–
Sylhet sand	kg/m^3	–	108.04	–	–	95.36
Sugarcane bagasse	kg/m^3	–	–	–	16.08	–
Biochar	kg/m^3	–	–	–	–	7.89
Electricity	kWh/m^3	0.67	1.65	1.70	1.70	1.67
Direct emissions to water						
TN	g/m^3	49.8	3.1	3.4	5.6	2.4
TP	g/m^3	3	0	0.5	1.6	0.5
COD	g/m^3	200	45.2	184	362.9	22.2

The frame of the designed CWs were constructed mainly using steel and PVC pipes. The PVC pipes were mostly used to build the VF units, and the HF units in all the systems, except those of S1 that were built with steel for durability and permanent use. Many materials were utilized as media materials, such as sand, mortar, brick, gravel, etc. The HF units of the CW systems required a larger amount of media materials due to the volume of the tank size compared to the VF units. The water quality parameters principally connected with eutrophication in the water resources were considered to characterize the CW systems, which were total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) [16]. Background datasets of the CW systems for the life cycles were chosen from the data inventory of ecoinvent 3.4. However, specific types of local materials like Sylhet sand and locally produced gravel not listed in the database were replaced by closely similar materials from the existing global ecoinvent database, listed as sand and gravel. Moreover, cupola slag, the byproduct created during steel production, is not available in the ecoinvent database; thus, scraped metal was chosen instead of slag. For electricity consumption during the system operation, low voltage electricity for Bangladesh was selected from the ecoinvent 3.4 database [20].

2.6. Impact Assessment

The LCA has been carried out for the potential environmental impacts using SimaPro faculty version 8.5, PRe′Sustainability, Amersfoort, Netherlands; while the ReCiPe 2016 (hierarchical version) method was chosen to conduct the LCA due to its impact measure on a global scale [20]. The impact assessment has been accomplished by utilizing mid-point and end-point categories to explain the findings. The impact assessment has been performed mainly focusing on climate change and human health due to the high impact of conventional treatment technologies on climate change phenomena [21]. Therefore, the following mid-point categories were considered to discuss the findings: global warming; fossil resource scarcity; human carcinogenic, non-carcinogenic, terrestrial, and freshwater ecotoxicity; and freshwater eutrophication.

2.7. Life Cycle Interpretation

Acknowledging that possible uncertainties may arise from the choice of method, we also conducted the LCA using an alternative method to look for possible differences or deviations in the assessment. Therefore, Impact 2002+ was chosen as an alternative method to cross-validate our findings obtained with ReCiPe 2016. The Impact 2002+ method is relatively new in assessing LCA studies for wastewater treatment and was applied by Lopsik [9]. In contrast, various studies to date have considered the ReCiPe method to apply LCA for different treatment technologies. In addition, to evaluate the effect of the inventory data on the overall LCA results, a sensitivity analysis was performed by varying ±10% of the media and construction materials data in the inventory. Sensitivity for the inventory components was calculated using Equation (1) by Zhou et al. [21]:

$$\text{Sensitivity Coefficient} = ((\text{Output high} - \text{Output low})/\text{Output default})/((\text{Input high} - \text{Input low})/\text{Input default}) \ldots \quad (1)$$

where input refers to the value of the inventory components, and output refers to the impact assessment results for any particular category.

Following sensitivity analysis, an uncertainty analysis was also conducted for the LCA results using a 1000-run Monte Carlo analysis for the CW systems under consideration. In uncertainty analysis, the inventory data has been assumed to be normally distributed.

3. Results and Discussion

3.1. Assessment of the Impact from the Usage of Different Types of Media in Constructed Wetlands for the Treatment of Industrial Wastewater

Depending on the source of the media and the ingredients that the media is composed of the chance of having a positive impact on the environment either increases or decreases. Thus, constructed wetlands using different media elements in varying configurations were evaluated to assess the impact through their usage. It also served as a basis for understanding the importance of collecting media from sources with a lesser environmental burden. Figure 2 portrays the comparative impacts of using different media in constructed wetlands with varying configurations.

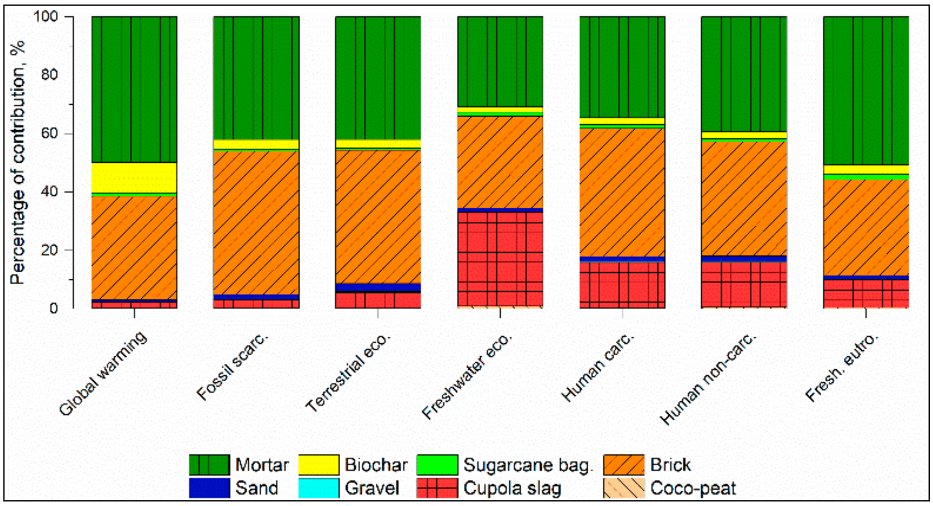


Figure 2. Comparative impact assessment of utilized media materials from their respective life cycles on selected categories.

In Figure 2, the impact of media materials is evaluated for seven categories focusing on climate and toxicity-related impacts. Primarily, brick and cement mortar seem to be the most impactful for every selected impact category. The impact categories, global warming and fossil resource scarcity, represent climate change and non-renewable energy usage, respectively, on which brick and cement mortar impart almost over 90% of the total impact compared to the rest of the media choices. As the inventory results show, for brick usage, the brick production process itself is the reason for high global warming, while around 60% impact is exerted from transportation. In the case of mortar, global warming mostly happens from clinker production and coal mining processes. These processes involve a high amount of carbon and methane emissions into the environment elevating the global warming scale. Meanwhile, biochar also significantly impacts (around 10%) total global warming input. High fuel injection through oil, coal, and natural gas usage during the production of mortar and brick are the reasons for high fossil depletion [14]. Concomitant to the high impact of cement mortar and brick on other categories, slag from steel industries as media materials contribute the highest (32%) to the imparting of toxicity into freshwater sources. The reason for this toxicity is the heavy leaching of copper and zinc into the water, while exposure to these heavy metals could cause human health toxicity. In contrast, media materials from natural sources such as coco-peat and sugarcane bagasse rarely significantly contribute to any of the impact categories. Hence, these materials are favorable options as media choices for CWs. However, breaking down the impacts from brick and slag, both materials are used in the CW systems in recycled forms. Bricks were collected from abandoned construction materials, and slag is the byproduct of the steel industries [16]. Therefore, the high impacts they contribute from their respective life cycles are not occurring due to their usage in CWs. The disposal of these spent items would have caused environmental damage, which is being prevented through its reuse in the CWs. On the other hand, cement mortar is used in high amounts, especially in the HF unit, as a filler material does not exert any environmental benefit provided the high impact it induces, while not contributing to the overall treatment.

An interesting thing to note is that using media materials in different wetland units (VF vs. HF units) in the same wetland brings significant differences in material consumption. This study refers to the usage of media materials sugarcane bagasse and brick in the VF and HF treatment units of wetland systems S3 and S4, respectively. Utilizing these media materials in the HF unit of a wetland can contribute around a ten times higher impact than the VF treatment unit. However, this might change according to the design scale of the treatment units.

3.1.1. Impact Assessment of the Overall Constructed Wetland Applications

Followed by the impact assessment of the life cycle of media materials, the overall impact evaluation of the constructed wetland systems as whole systems is presented in the sub-sections as illustrated in Figures 3 and 4. The results are represented here under mid-point categories to avoid possible uncertainties [22]. Although it certainly is a challenge to compare the variability in impact due to multiple operational variables, an overall impact assessment paves the way towards realizing the optimum and favorable conditions with minimal environmental obliteration.

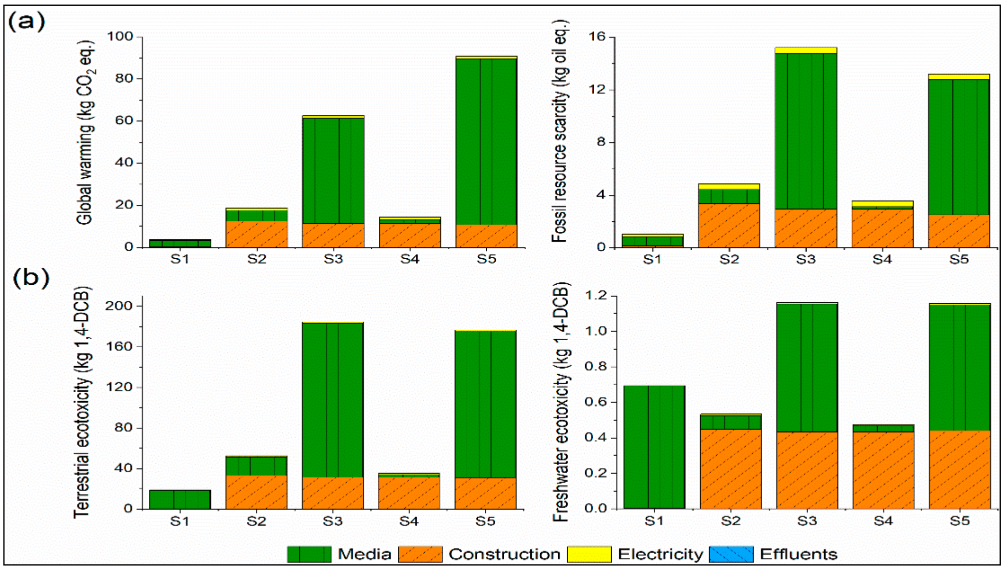


Figure 3. Impact on (**a**) global warming, fossil resource scarcity, and (**b**) terrestrial, freshwater ecotoxicity categories, during the overall life cycle of CWs.

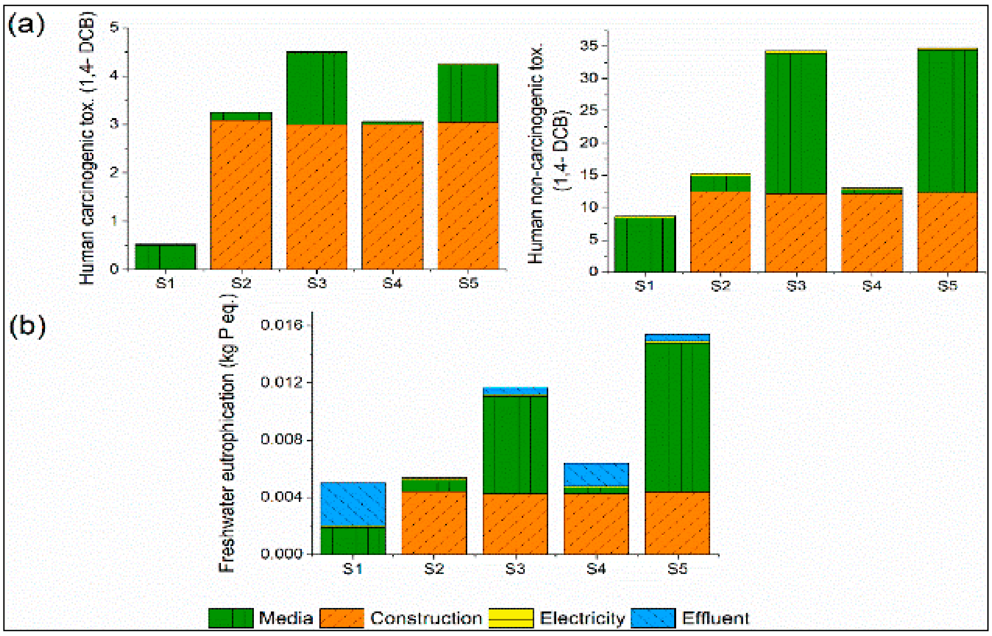


Figure 4. Impact on (**a**) human carcinogenic, no-carcinogenic toxicity, and (**b**) freshwater eutrophication, during the overall life cycle of CWs.

3.1.2. Global Warming and Fossil Resource Scarcity

Figure 3a shows that the global warming and fossil resource scarcity categories are influenced mainly by the CW systems' media and construction materials. The systems S3 and S5 exert the highest levels of impact in both the impact categories. Both systems are equipped with media materials, such as brick and cement mortar for treatment operation, which have been previously shown as highly impactful media materials for climate-related categories, ultimately impacting the overall assessment, as evident here. Impacts from construction materials cause global warming, while fossil fuel usage is primarily due to steel, through its production, coal operations, and mining, required for the steel industries. System S1 contributed the least for both impact categories; notably, the system does not significantly impact the construction materials as it did not require any steel for building the system. In addition, S1 employed media materials from natural sources like coco-peat, and thus caused the scale to be the lowest among all the CW systems. Likewise, the employment of sugarcane bagasse as media materials was the reason for a lower-level impact on overall counts for S4. However, S2 surprisingly shows a comparatively lesser impact on both categories than S3 and S5, despite using brick and mortar as media materials. The explanation is linked with the media categories that the systems utilized, as brick and mortar were employed in the VF unit to have fewer materials than the HF unit, ultimately leading to the lifting up of the impact scale as specified in the earlier section. Apart from the impact of construction and media materials, electricity consumption has a significantly less contribution on the global warming and resource depletion categories for all the CW systems.

Previously, Lopsik [9] observed a high impact on global warming from the CW than from activated sludge wastewater treatment systems and attributed that to the construction materials and media used in the system. Those findings are aligned with our present study findings, that a high contribution to global warming is the result of the construction and media materials utilized in CWs. However, compared to the results of the LCA findings by Flores et al. [11] for large-scale CW systems, the present study shows a substantial score for both categories. This is obvious as the present study considers laboratory-scale designs with low-flow rates consuming the highest amount of materials and electricity against the functional unit. Even the present findings exceed the impact scores for conventional treatment plants reported by Niero et al. [20] to treat a single unit (m^3) of wastewater. Therefore, to build effective and sustainable CW treatment set-ups, system capacity needs to be high, along with suitable materials to be utilized in designing and building the system.

3.1.3. Terrestrial and Freshwater Ecotoxicity

In harmony with the findings for climate-related categories, systems S3 and S5 also exert a high impact on terrestrial and freshwater toxicity categories, as shown in Figure 3b, with impacts primarily due to the media and construction materials. From the inventory, the processes involved cause terrestrial and freshwater toxicity in brake wear emissions during the transportation and offsite sulfidic tailing. These processes expose a high amount of Cu and Zn into the air and water, eventually triggering toxicity for freshwater and terrestrial surroundings. In the case of terrestrial ecotoxicity, S1 shows the most negligible impact, whereas, for freshwater toxicity, impact scores for the same system are elevated, being the third highest among the CWs.

As ReCiPe 2016 publishes toxicity categories in a uniform unit of 1,4-dichlorobenzene, terrestrial toxicity scores were high for the CW treatment systems' life phases. This is certainly attributed to the media material slag, which was previously proved to be the highest contributor to inducing toxicity into freshwater environments through spoils and residues from different operations. Meanwhile, discharged effluents and electricity consumption have not been noticed to have any notable impact.

3.1.4. Human Carcinogenic and Non-Carcinogenic Toxicity

Similar to the trends observed for all the considered categories, S3 and S5 again impart comparatively higher impact for human carcinogenic and non-carcinogenic health issues than the other CWs, as shown in Figure 4a. As suggested by the results, processes involved in carcinogenic health risks are primarily from the production phases of steel and spoils thrown into landfills exposing water and air to high levels of chromium (VI). Considering human carcinogenic toxicity, construction materials are responsible due to the use of steel to build frames. The finding supports the explanation that S1, which has no steel in its construction process, exerts the lowest impact. In the case of non-carcinogenic toxicity in human bodies, impact count is primarily explained by the media than the construction materials for S3 and S5. The processes mainly involved mining work to extract materials for brick and cement production. However, the construction material steel is contributing highly in S2 and S4 primarily due to zinc leaching into the water from the processes involved in steel production (over 90% of the total contribution). The impact from media materials has significant incongruity for both the human toxicity categories; notably, S3 and S5 have the highest contribution from media, while S4 has the least. Therefore, using media materials cement mortar and brick pose the highest threat to carcinogenic and non-carcinogenic human health risks [11]. In addition, less energy in operating the systems caused electricity to have an almost negligible contribution.

3.1.5. Freshwater Eutrophication

Because of the discharge of treated wastewater into local freshwater resources, the chances are high that nutrients will cause freshwater eutrophication, and the impact is shown in Figure 4b. However, the other category, marine eutrophication, has been omitted here as it is not relevant to the scope of this study.

According to Figure 4b, the eutrophication impact exerted from the life cycle of the CW systems ranged between 0.005 to 0.015 kg P eq. Comparatively, the systems S3 and S5 exert the highest ratings on the scale (0.011 and 0.015 PO_4^{3-} eq. respectively). These impacts are mainly from media materials, followed by construction materials. Significant contributions to eutrophication impact from construction materials were also obtained in previous studies [1,8], besides effluent discharge. Induced eutrophication from all systems comes from the spoils of coal mining and oxygen furnace waste from steel production. Coal mining is required as part of steel production and within the life cycle of some media materials, such as cement mortar and brick. The total phosphorus, phosphate, and phosphorus through the mentioned processes within water and soil contribute to the results on eutrophication impacts. In contrast, the lowest impact among all the CWs is observed in S1 (0.005), noticeably due to the minuscule contribution from the construction materials. Meanwhile, no eutrophication threat has been contributed from the discharge of S2, probably due to the application of a three-stage treatment, eventually increasing the system's efficiency. However, with similar three-stage employment, system S1 proved to cause the highest impact on eutrophication from treated wastewater. As Table 3 demonstrates the comparative impact of raw and treated wastewater on eutrophication among the different CW systems, the removal efficiency stands were around 90% for system S1, although the end discharges were still high for eutrophication potential due to the discharge of wastewater enriched with high nutrients from the tannery industries. In terms of reducing the impact from raw to treated wastewater, system S2 can perform the best, maintaining 100% efficiency for industrial wastewater inputs. Conversely, S4 has the lowest efficiency while utilizing sugarcane bagasse as media materials. Although sugarcane bagasse was proved to be comparatively the more sustainable option for media usage earlier, it did not function with unlimited potential in wastewater treatment. The only CW system S5 dealing with municipal sewage also maintained excellent efficiency, providing a treatment performance of around 96%, which used mortar as the media. Nevertheless, from a sustainability of the environment perspective, the usage of mortar as a media material should be avoided despite providing effective treatment operation.

Table 3. Comparative aquatic eutrophication impact from raw and treated wastewater of the different constructed wetland systems and treatment performance.

CW System	Raw Water Impact on Freshwater Eutrophication (kg P eq.)	Treated Water Impact on Freshwater Eutrophication (kg P eq.)	Treatment Efficiency (%)	Types of Wastewater Treated
S1	0.0300	0.0030	90.00	Tannery
S2	0.0023	0.0000	100.00	Industrial
S3	0.0046	0.0005	89.13	Industrial
S4	0.0046	0.0016	65.22	Industrial
S5	0.0141	0.0005	96.45	Sewage

Meanwhile, brick also exerts a contribution to eutrophication during its life period. However, since brick is used as a recycled residue from abandoned building materials, it is beneficial for the environment to redeem the previous impact of bricks during the production stage. A previous study [23] showed that the eutrophication impact from influent and effluent was nearly reduced from 95% to 63% by six different wastewater treatment plants. Thus, regardless of the variability in the sources of the wastewater and treatment system employed under the current study, treatment efficiency within the range of 65% to 100% in comparison with previous studies implies the stable, robust, and consistent performance of the CWs.

3.2. Assessment of the Impact from Constructed Wetland Systems for Landfill Leachate from Municipal Solid Waste

The current research aims to provide a sustainability-based justification for the use of constructed wetlands for the treatment of heavy metals in leachate after having investigated the treatment viability of four heavy metal parameters using such systems. Utilized CW systems have therefore undergone an LCA study taking into account the materials used and the life phases they went through during their operating duration. Results from the life cycle assessment have been broken down into damage and median. Discussion of the ecological viability of the built wetland treatment method is further extended in the following sections, which discuss the LCA results in further depth.

3.2.1. Damage Categories

Based on 15 intermediate categories that were linked to 4 damage categories, Impact 2002+ calculated the impact. Using Impact 2002+, the results are validated into different impact categories as well as into the damage categories at the level of damages to human health, the natural environment, and natural resources via damage indicators. The damage categories serve as endpoint methods that refine the original 15 midpoint impact categories into 4 more specific indicators that measure environmental damage. Figure 5a,b represents the life cycle impact assessment on the four damage categories for two different CW systems.

Figure 5a,b shows that the greatest impact on human health is in the occupational category for both CWs, whereas effluent emissions have a comparatively little effect on the other three categories. Therefore, it is safe to assume that both CW systems operate adequately, while employed with appropriate and safe design elements. To counter this, CW A_2-B_2 attributes the most harm to human health, mostly due to the media materials followed by the building materials. When comparing the long-term effects of systems A_1-B_1 and A_2-B_2, the media material predominates since both CWs have a comparable effect on the human health category for building supplies. Consequently, brick as a media material provides a greater risk to human health than coco-peat used in systems A_1-B_1 and A_2-B_2 [24]. Furthermore, bricks affect the CW A_2-B_2, first in the area of climate change and ultimately, in the area of resource usage, leading to a greater impact score. Brick production and mineral extraction for the raw materials contribute significantly to greenhouse gas emissions, which may be the root cause [25]. This means that the effect of systems A_2-B_2 would be greater, owing to the use of brick as the media material.

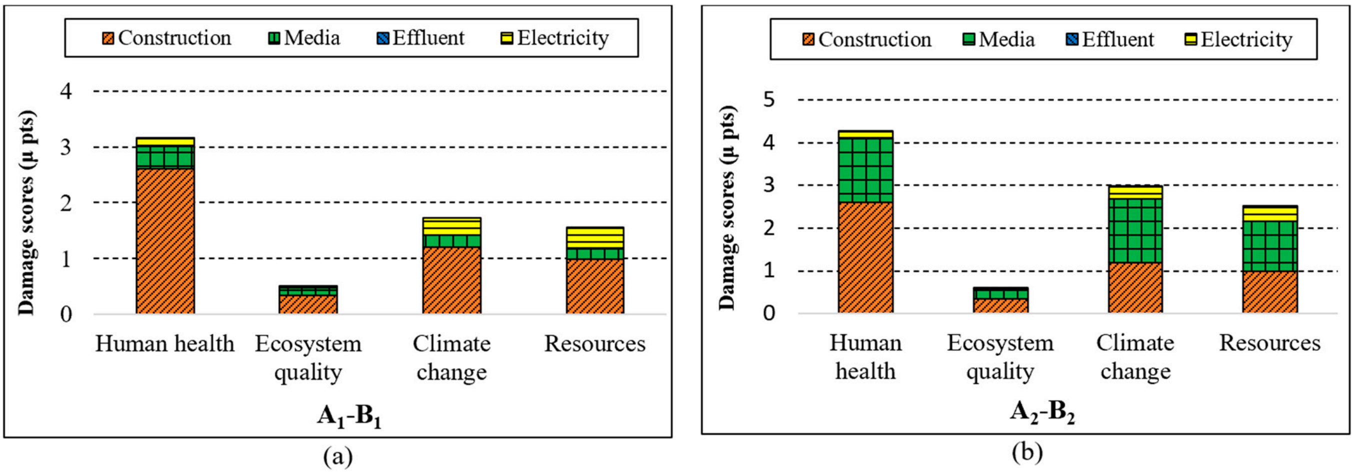


Figure 5. (**a**,**b**). Life cycle impact assessment on four damage categories for (**a**) A_1-B_1, and (**b**) A_2-B_2, CW systems.

3.2.2. Mid-Point Categories

This study's main interest is the effect that heavy metals have on ecosystems after they have been treated and released from treatment systems, thus we begin by detailing the impact assessment on the damage categories before moving on to a more detailed examination of the effect in the following sections. To verify the results of the present study, 3 of the 15 middle-range categories—"Aquatic ecotoxicity," "carcinogens," and "non-carcinogens"—were chosen.

Aquatic Ecotoxicity

Figure 6 shows the results of the impact assessment for the aquatic ecotoxicity category, which included the evaluation of two constructed wetland systems throughout four stages of their life cycles. Here, the Impact 2002+ approach using SimaPro yields findings expressed in terms of kilograms of TEG water.

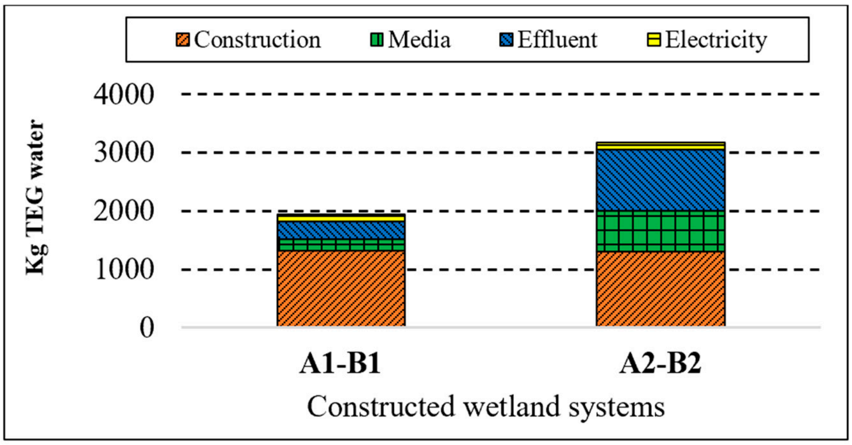


Figure 6. Impact assessment on aquatic ecotoxicity for two different CW systems.

Figure 6 shows that the A_2-B_2 system is particularly contributing to aquatic ecotoxicity because it includes impacts on all four categories (construction, media, effluent, and electricity), with the least impact on electricity. Both systems of wetlands exert a significant impact from construction, while system A_2-B_2 exerts notable impact through its effluent quality than the other system. Both the CW systems used comparable design principles and feeding rates to operate the pumps; therefore, the contributions from the building materials and power were almost the same.

Carcinogens

Human exposure to a carcinogen is defined by how likely the person is to develop cancer. The cancer-causing effects of the life cycle of the two CW systems considered in this research are shown in Figure 7.

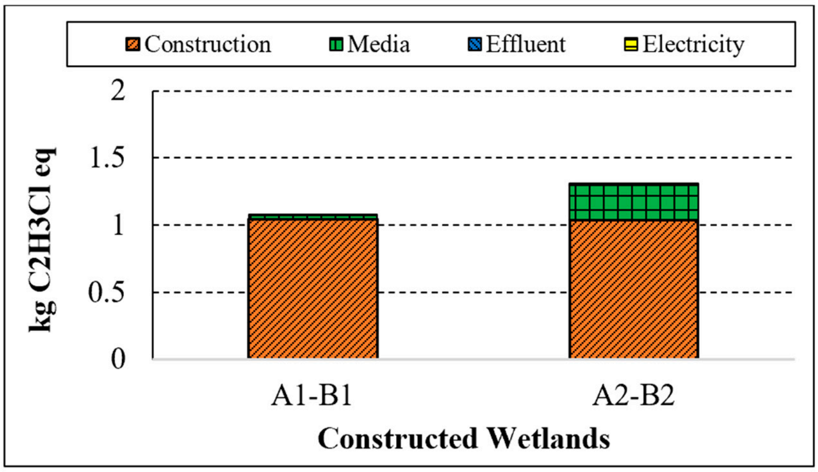


Figure 7. Impact assessment from carcinogens for two different CW systems.

Figure 7 shows that treated effluent does not seem to represent any substantial concern under our current methods, since it does not exert any impact on the carcinogen category. However, steel as a building material poses a serious carcinogen hazard in the construction category, most likely because of the variety of alloys and processes involved in its production. In addition, with regards to media, compared to coco-peat, the effect of using brick as the A_2-B_2 media seems significant.

Non-Carcinogens

Impact categories that do not cause cancer in humans but offer potential health risks are referred to as "non-carcinogens". Figure 8 demonstrates the non-carcinogenic effects over the whole life cycle of the CW treatment systems.

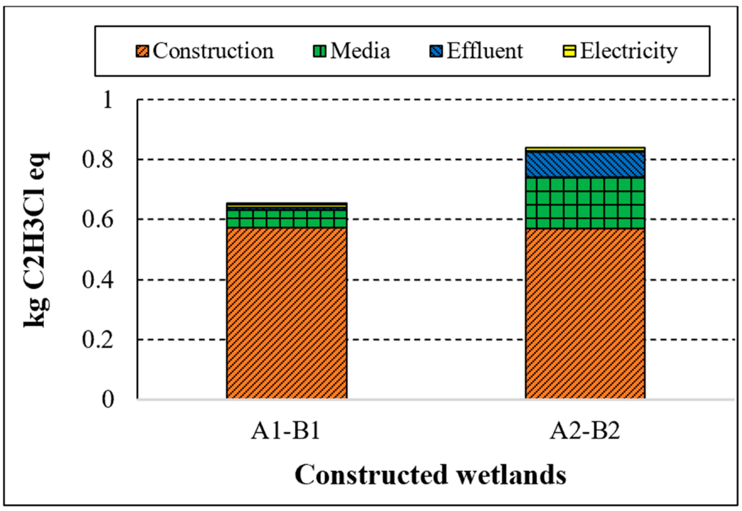


Figure 8. Impact assessment from non-carcinogens for two different CW systems.

The majority of the impact exerted by both CW configurations is contributed by the materials used in their construction. The reason for the significant contribution is the use of steel in the frame's construction (Figure 8). The influence of media is greatly amplified by brick [23], the media material of choice in system A_2-B_2. Effluent emission is also contributed notably by system A_2-B_2; however, system A_1-B_1 has almost negligible contribution in effluent emission. As a result, except construction impacts, the A_1-B_1 system in general demonstrates superior performance in regard to exerting non-carcinogenic impacts on the environment [26].

3.3. Sensitivity of the Different LCA Methods on the Overall Impacts

Since different LCA methods have been used in practice and have been applied in previous studies to conduct the LCA of wastewater treatment technologies, it should be a point of interest to perform the assessment using an alternative method to evaluate the possible deviation that might arise before confirming the outcomes. Hence, the present study employed another method, Impact 2002+, besides ReCiPe 2016, to evaluate the possible differences between these two methods. The comparisons are made utilizing the previously selected categories and are explained in Figures 9 and 10, for climate change, toxicity, health, and eutrophication impact categories, respectively.

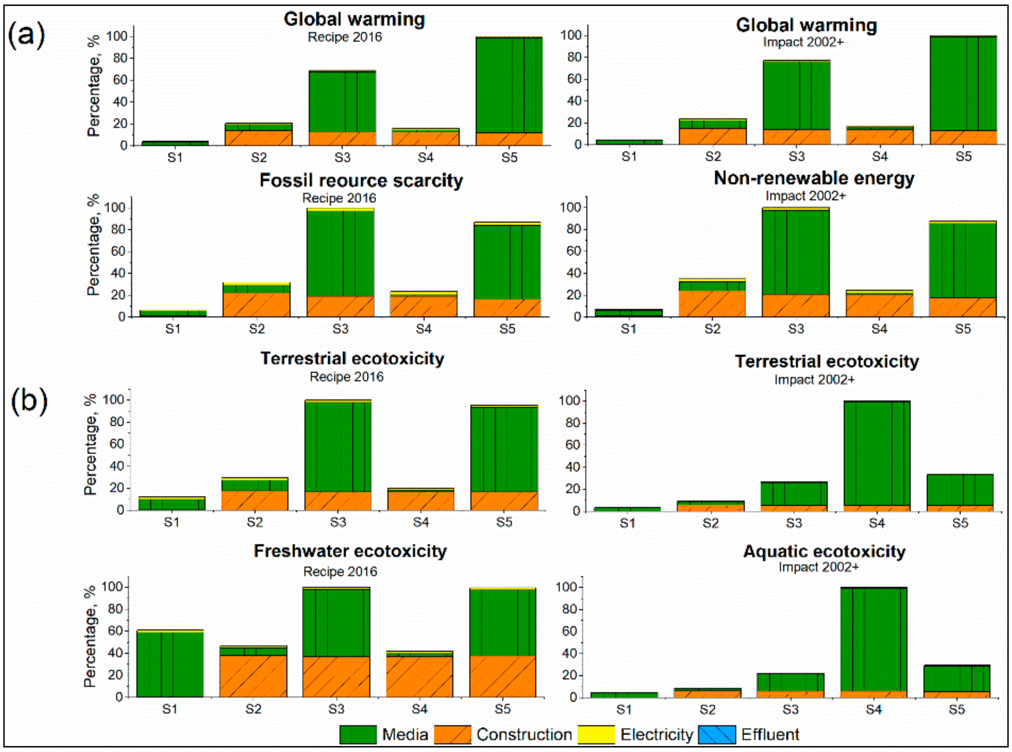


Figure 9. (**a**,**b**). Comparative scenario of the ReCiPe 2016 and Impact 2002+ methods on (**a**) climate change, energy consumption; and (**b**) terrestrial, freshwater toxicity, related categories.

Global warming is the common category for measuring greenhouse gas emissions in the Impact 2002+ and ReCiPe 2016 methods. Both methods utilize the standard unit of kg CO_2 into the air, following the IPCC guidelines [22,23]. Looking at Figure 9a, the evaluation of global warming through both methods does not present any noticeable change. Another important category, fossil resources scarcity, has been considered to measure the limited fossil fuel consumption from the life cycles of our present CW system. On a similar note, Impact 2002+ measures the consumption of the non-renewable fuel usage with the category of non-renewable energy. The methods available for the LCA assessing global warming and resource depletions are similar, as reported by a previous study [27]. The comparative assessment also portrays almost similar impacts for both methods.

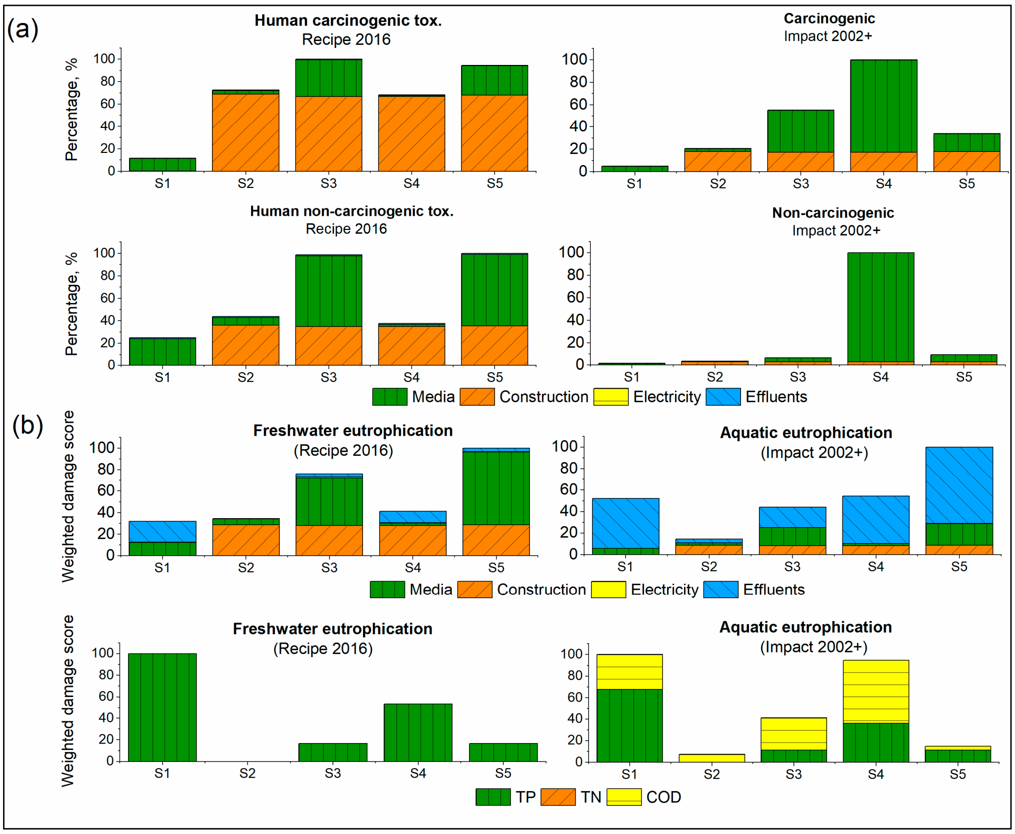


Figure 10. (**a**,**b**). Comparative scenario of the ReCiPe 2016 and Impact 2002+ methods on (**a**) human health categories; and (**b**) eutrophication.

For toxicity measures of terrestrial and freshwater sources, apparent differences are pronounced between ReCiPe 2016 and Impact 2002+, as shown in Figure 9b. While systems S3 and S5 contribute towards most of the impact proportions with ReCiPe 2016, Impact 2002+ indicates that system S4 causes the highest burdens for both terrestrial and freshwater toxicity categories. As our inventory data suggests, Cu exposure to the environment through the air and water is explained for over 70% of the overall impact on terrestrial ecotoxicity. However, for Impact 2002+, the category terrestrial ecotoxicity is mainly dominated by Zn and Al, with over 40% of the total contribution and primarily from S4. However, in terms of the processes contributing to the impact, brake wear emissions from transportation and other related causes constitute the primary reasons for causing the high impact on terrestrial ecotoxicity in both methods.

For freshwater ecotoxicity, the significant contribution is exerted by Zn (over 60%), primarily from the process sulfidic tailing causing the highest impact for S3 and S5 using ReCiPe 2016. In contrast, exposure to Al in soil and water contributes over 40% of the total aquatic toxicity using Impact 2002+, which eventually does not have any impact on ReCiPe 2016 [28]. In the case of Impact 2002+, the sugarcane production stage is regarded as the primary reason for the significant leap in the toxicity scale from S4, which has been overlooked in ReCiPe 2016. Therefore, different processes involved with varying coverage on substances eventually cause the differences in the resulting variation in the assessment by ReCiPe 2016 and Impact 2002+.

Concomitant with previous toxicity categories, S4 imparts the highest impact for carcinogenic and non-carcinogenic categories, according to the Impact 2002+ assessment (Figure 10a,b). The process responsible for this high impact is sugarcane production, exposing high arsenic levels to the soil.

However, for ReCiPe 2016, chromium (VI) in water is most possibly the primary contributor (over 90%) for carcinogenic toxicity, the opposite to zinc in water, that might have caused the non-carcinogenic toxicity in the life cycles of the CWs. While the exposure of chromium (VI) was not evident in Impact 2002+, no arsenic exposure had been detected in the data inventory for ReCiPe 2016. Therefore, similar to previous toxicity categories, different substances causing the impacts are also evident for human health toxicity categories. Hence, the present observation confirms the conclusion of previous studies [22] that the choice of the assessment method is the reason for varying the impact scores for toxicity categories.

Figure 10b shows a comprehensive scenario of eutrophication's impact on the overall life cycle of the CW systems and the contribution from nutrients, respectively. As presented in Figure 10b, the considerable differences between the two methods are the contribution of discharged wastewater and eutrophication impact. In the case of ReCiPe 2016, the total eutrophication score has been impacted less by discharged effluent; however, Impact 2002+ depicts the significant contribution from effluent. Differing from ReCiPe 2016, Impact 2002+ uses PO_4^{3-} as a reference substance for estimating the aquatic eutrophication impact category. In this method, freshwater and marine eutrophication are aggregated into a single category; hence, differences in impact count between the two methods are apparent. Analyzing the inventory data contributing to the impact as presented in Figure 10b, the aquatic eutrophication for Impact 2002+ can be caused by phosphate, total phosphorus, phosphorus, phosphoric acid, and chemical oxygen demand (COD). At the same time, COD has not been considered in ReCiPe 2016 method. From the overall life cycles, phosphate emission has been considered the highest contributor to eutrophication for most systems in both methods. However, an interesting fact to notice is phosphate and phosphoric acid have been considered to impact eutrophication through the air, soil, and water in Impact 2002+, but for ReCiPe 2016, substances through the air have not been considered to influence the eutrophication count. Thus, it is evident that different models have been considered by these two methods to calculate the eutrophication potential.

3.4. Sensitivity Analysis of the Inventory Components

Table 4 lists the sensitivity analysis results varying all the inventory information on the media and construction materials by ±10%. However, only majorly impacted components are listed here, and the detailed sensitivity analysis result for each component is presented in Supplementary Table S1. Inventory components influencing the results over 5% are shown in bold in Table 4.

Table 4. Impact categories influenced by varying ± 10% of the selected inventory components.

CWs	Parameters	Impact Categories Global Warming	Terrestrial Ecotoxicity	Freshwater Ecotoxicity	Human Carcinogen	Human Non-Carcinogen	Fossil Scarc.	Freshwater Eutro.
S1	Slag	**±0.416**	**±0.733**	**±0.934**	**±0.922**	**±0.910**	**±0.342**	**±0.353**
	Gravel	±0.063	±0.119	±0.013	±0.033	±0.035	±0.065	±0.017
S2	Steel	**±0.440**	**±0.524**	**±0.775**	**±0.903**	**±0.780**	**±0.299**	**±0.798**
	PVC	±0.169	±0.079	±0.043	±0.046	±0.041	±0.312	±0.023
	Mortar	±0.120	±0.088	±0.045	±0.012	±0.050	±0.064	±0.068
	Brick	±0.094	±0.106	±0.051	±0.017	±0.055	±0.082	±0.048
S3	Steel	±0.136	±0.151	**±0.352**	**±0.642**	**±0.339**	±0.102	**±0.358**
	Brick	**±0.776**	**±0.811**	**±0.613**	**±0.328**	**±0.637**	**±0.613**	**±0.579**
S4	Steel	**±0.543**	**±0.742**	**±0.845**	**±0.940**	**±0.890**	**±0.381**	**±0.656**
	PVC	±0.162	±0.087	±0.037	±0.038	±0.037	**±0.310**	±0.015
	Bagasse	±0.110	±0.068	±0.051	±0.016	±0.047	±0.044	±0.056
S5	Biochar	±0.145	±0.049	±0.032	±0.016	±0.033	±0.050	±0.040
	Steel	±0.098	±0.163	**±0.366**	**±0.701**	**±0.346**	±0.120	±0.127
	Mortar	**±0.695**	**±0.711**	**±0.549**	±0.249	**±0.576**	**±0.666**	**±0.617**

According to Table 4, the steel material used to build the frames of the CW seems commonly sensitive in all the systems from S2 through to S5 except for S1, which did not utilize any steel in building the system. The results show that for S1, the utilization of slag as the media material is most sensitive in every impact category. Especially for human toxicity categories, the sensitivity coefficient is around 0.9, which suggests that a 10% variation in the use of slag will impose a variation on human health impacts by around 9%.

For S2 and S4, steel impacted the results widely for all the categories, significantly for toxicity-related categories by over 5% if the inventory data are varied by 10%. The use of brick as the media material for S3 impacts highly on global warming (around 7%) and is sensitive widely for all the categories. Likewise, the use of mortar also proved sensitive for most of the categories in the case of S5. However, other media material, such as PVC, has not shown any significant impact, and is thus not included in Table 4.

Apart from the construction and media materials in the inventory, electricity, and total phosphorus (TP) from the discharged water have not been marked as sensitive except in system S1. Here, TP from the discharged wastewater caused freshwater eutrophication to vary by 6% if the TP emissions differed by 10% from the default data.

Inferences from the sensitivity analysis are such that steel usage for constructing the frame of the systems is highly influencing the environmental burdens from the CW systems, along with media choices like brick, mortar, and Sylhet sand. However, the findings here should consider that the slag and brick were used as recycled materials, eventually proving beneficial for the environment.

3.5. Uncertainty Analysis

Following the sensitivity analysis, an uncertainty analysis has been performed, taking all inventory components of the CW systems into account, as shown in Table 5. According to Table 5, the coefficient of variation (CV) of the impact categories from the LCA application has been found to be below 10% for normally distributed inventory data.

Table 5. Results of uncertainty analysis of inventory components under LCA application of CW.

CWs	Parameters	Impact Categories						
		Global Warming	Terrestrial Ecotoxicity	Freshwater Ecotoxicity	Human Carcinogen	Human Non-Carcinogen	Fossil Scarc.	Freshwater Eutro.
S1	CV	±7.09%	±8.58%	±9.28%	±9.17%	±9.50%	±6.46%	±9.44%
	CI	±0.44%	±0.53%	±0.58%	±0.57%	±0.59%	±0.40%	±0.59%
S2	CV	±5.04%	±5.81%	±7.73%	±9.05%	±7.81%	±4.87%	±8.01%
	CI	±0.31%	±0.36%	±0.48%	±0.56%	±0.48%	±0.30%	±0.49%
S3	CV	±8.21%	±8.28%	±7.35%	±7.74%	±7.27%	±7.83%	±6.87%
	CI	±0.51%	±0.51%	±0.46%	±0.48%	±0.45%	±0.49%	±0.43%
S4	CV	±6.79%	±7.93%	±8.59%	±9.45%	±9.33%	±5.76%	±6.88%
	CI	±0.42%	±0.49%	±0.53%	±0.59%	±0.58%	±0.36%	±0.43%
S5	CV	±7.40%	±7.36%	±6.67%	±7.62%	±6.49%	±7.10%	±6.81%
	CI	±0.46%	±0.46%	±0.41%	±0.47%	±0.40%	±0.44%	±0.42%

However, the 95% confidence interval most significantly varied below 1% in selected impact categories for CWs. This is suggestive of limited uncertainties involved in the inventory components from the CWs on the LCA results.

4. Conclusions

This study portrays the environmental impacts associated with the application of different configurations of constructed wetlands for wastewater and landfill leachate treatment. Different configurations of previously established lab-scale wetlands have been considered for impact analyses. In addition to measuring the impact assessment from the overall life cycles of the considered wetland systems, comparative impacts of the utilized media materials, the contribution to eutrophication aside from the treatment performance, and the contrasting representation of the contaminant reduction benefit versus the environmental damage scores from the CW systems, have been detailed in this study. Regardless of the heterogeneity in wastewater sources and treatment systems used in the current study, treatment efficiency within the range of 65% to 100%, in contrast with prior studies, suggests the reliable, robust, and consistent performance of the CWs. The results showed that cement mortar and brick have the highest impact (over 90%) for almost all the selected impact categories among the media choices. In contrast, sugarcane bagasse has been comparatively the most environmentally friendly option. Thus, it is recommended by this study that the usage of cement mortar should be avoided as a treatment option and replaced with other potential options. However, if brick chips can be utilized from abandoned building materials, as it stands for the present study, then certainly it is the best sustainable way to redeem the environmental burdens from the life cycle of brick. Among the construction materials, steel poses a much higher environmental threat for all the categories than PVC pipes. Nevertheless, design criteria significantly differ in the impact score concerning the configurations of the VF and HF units. The system using brick and cement as media materials in the VF treatment unit has a shallow impact compared to the systems utilizing the same media in the HF units. Hence, design criteria can lead toward environmental balance if adequately addressed. Although cement and brick have high impact scores, these materials provided excellent treatment efficiencies in the CW systems. In comparison, the most environmentally friendly option, sugarcane bagasse, has the lowest efficiency for treatment. On the negative side, the environmental impact of the CWs has been assessed using laboratory-scale units. Thus, the comparative impacts are significantly higher than the real-life applications represented in previous studies. Nevertheless, the present study explored impacts from different media materials and design approaches, which have yet to be distinguished in attempted studies. Hence, this study could serve as guidance in designing CW set-ups aimed at sustainable treatment performance. Environmental exposure to Cu via the air and water accounts for more than 70% of the total effect on terrestrial ecotoxicity. Nevertheless, Zn and Al, accounting for over 40% of the overall contribution, dominate the category of terrestrial ecotoxicity for Impact 2002+. After comparing Impact 2002+ and ReCiPe 2016 methods for the impact assessment of the CWs, a significant difference is noticeable for the toxicity and human health categories as different models have been implemented in these methods. However, both methods' results have been almost identical in the case of global warming and energy utilization.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w15050909/s1, Figure S1: Flow Diagram of constructed wetland system (S1) for treatment of industry wastewater using construction materials; Figure S2: Flow Diagram of constructed wetland system (S2) for treatment of industry wastewater using construction materials; Figure S3: Flow Diagram of treatment of constructed wetlands (S3 and S4) for industrial wastewater treatment using construction materials and agricultural by products; Figure S4: Flow Diagram of constructed wetland system (S5) for removal of nutrients from sewage without any flow direction controlling unit; Table S1: Impact categories influenced by varying ±10% of selected inventory components.

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