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Analysis the potential of online tools to support the design of constructed wetlands

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ABSTRACT

The development of effective methods to treat municipal wastewater is the current challenge of sustainable water management, the problem is particularly important and common in developing countries, but also applies to developed countries (e.g., in areas with scattered housing). Constructed wetlands are a solution with a particularly high potential to fulfill this need, especially as they are characterized by simple construction, reliability, economic performance and low electricity consumption. However, a huge challenge in their dissemination is the lack of comprehensive and credible design guidelines, generally reliable sources of knowledge for decision-makers and designers. The article analyzes barriers and needs in this respect and presents an online tool, that is, the Constructed Wetland Knowledge Platform. The article also analyzes the current resources of this platform, especially their potential and usefulness for designers of wastewater treatment solutions. The analyzes carried out in the article have shown that tools of this type can provide significant support in the selection of appropriate design solutions, as well as in professional designing of constructed wetlands. Thus, constituting a valuable tool for popularizing this solution in the world, as well as their practical application in various environmental, climatic, technical and even social conditions.

Keywords: Constructed wetlands; Constructed Wetland Knowledge Platform; Sustainable sanitation; Wastewater management; Internet platform

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1. Introduction

Constructed wetlands (CWs) are engineering systems based on natural process. This involves wetland vegetation, soils and the associated microbial assemblage to assist in treating wastewater [1,2]. The processes involved in pollutant removal are sedimentation, sorption, precipitation, evapotranspiration, volatilization, photodegradation, diffusion, plant uptake and microbial degradation, etc. [3,4]. CWs have been proven to be effective, attractive and sustainable alternative for the conventional wastewater treatment technology for small community (less than 5,000 equivalent

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persons) [5,6]. They have low operating and maintenance requirements compared to other technologies, and are robust in the sense that their performance is less affected by the variations of influent flow rate, as well as the load of contaminants [7,8]. CWs takes advantages of natural process to remove pollutants from the water, generally avoiding the use of chemical products and the input of high amount of external energy [3,9], which is especially important in the context of climate change and energy crises [10,11].

Besides treatment, CWs can provide a broad range of additional ecosystem services, such as improving biodiversity and environmental conditions related to wildlife, irrigation of agriculture lands, improving the quality of surface and ground water or riverine restoration [3,10]. CWs have been shown to be effective in improving the water quality of different types of effluent; raw, primary, secondary or tertiary wastewater and different types of agricultural and industrial wastewater [7,9]. Originally, CWs were designed to treat domestic wastewater, but in recent times they are being used in many sectors and industries, such as mining, petrochemical, dairy, meat processing, abattoir, pulp and paper factory, tannery, brewery, and even to treat acid mine wastewater and landfill leachate [2,4,7,12].

Langergraber et al. [13] also point to other potential multi objectives for which CWs could be designed: retaining water to store it to later evapotranspire it or attenuate flood waves; evapotranspirating water which is key for sludge treatment, but also for cooling and reducing urban heat islands effects; producing of biomass; harvesting nutrients; creating an esthetics landscape, including for recreational purposes; enhancing ecosystems services, fostering biodiversity, directly or by creating habitats.

However, there is no consensus way to design a CW, Dotro et al. [7] note that, over the past few decades, design approaches have evolved from a simple rule of thumb to regression-based approaches and even more advanced calculations that include factors such as hydraulic loading rate, non-ideal flow, background concentration. In any case, it is important to consider that any design should take into account the parameters that are based on data from systems that have been operating at full scale [14]. Thus, it is necessary to provide the complex guidance to facilitate the technical implementation of constructed wetlands, for which this article proposes the virtual tool – Constructed Wetland Knowledge Platform (CWKP), based on successful experiences in wastewater treatment using this solutions. The article also analyzes the current content of the platform database, especially the correlations between different parameters stored in CWKP to show how a type of CWs and their other technical features influence the removal efficiency of the key wastewater quality parameters. Such analyses are crucial to show the potential of online tools and the possibility of their use for professional selection and design of CWs, with due regard to specific needs and requirements. Which, in turn, is crucial for the sustainable development of this technology and its stable and authentic popularization.

CWKP, analyzed in the article is an online platform (https://data.cwetlandsdata.com) on constructed wetlands that includes a database and a web-based geographic information system (WebGIS), being created within the framework of the project "Towards the 'Constructed Wetlands Knowledge Platform' for sustainable development" (CWetlands Data). CWKP is an open-source knowledge platform of selected CW data and information that provides a global system for standardized data collection and management. It is a visual and user-friendly platform with dynamic maps and an intuitive and efficient mechanism for uploading and downloading, including the quality control of CW-related data. It also provides statistics on key data in an interactive format, as well as guidance and documentation on CWs and links to information and educational resources. Up to 134 different parameters can be recorded for each CW system, allowing detailed conclusions to be drawn about structure and performance of each CW. The data is stored in a database and can be exported in various table formats (e.g., CSV and XLS). So far, the database contains 197 entries and 198 users (the 1st August 2022), but by the time the project "CWetlands Data" ends, there will be data records for more than 300 CWs included.

A general framework for WebGIS development that can be adopted for several projects does not exist, but there are some project-specific methodologies such as the Y-model WebGIS development methodology, presented in Fig. 1 [15]. Database development usually involves a requirement analysis as well as conceptual, logical and physical designs [16].

Finally, CWKP intends to build a science-based worldwide network with a focus on Latin America. The nucleus of the project is a close cooperation among and between CELAC partners (Peru, Guatemala and Uruguay) and European countries (Germany and Poland) within the project, each with their unique and specific strengths and capacities. Based on the Y-model, CWetlandsData focuses in the following three areas: (1) understanding user needs and gathering feedback; (2) developing the database and data collection; (3) developing the visual elements and prototyping the platform.

CWKP is already in the final phase, but the project partners are always open for improvements. Originally, United Nations University, Institute for Integrated Management of Material Fluxes and of Resources initiated the development of a CWKP database, in collaboration with CentroGeo, a private company in Mexico. In a global user requirements survey, about 30% of the respondents were from the CELAC region. Respondents from the CELAC region specifically requested in the survey that a database containing CWs should fulfil the following objectives: (1) comparison of data for feasibility and design studies; (2) teaching character; (3) monitoring and reporting; (4) model building and testing; (5) provision of well-supported figures for users. The basic data collection was further developed into a real database based on a more professional structure at the Institute of Botany, Leibniz University Hannover (LUH) together with database specialists at the L3S, LUH to taken into account the requirements of the users. All parameters that the database should have were defined and incorporated in CWKP structure. Some preliminary data from the first data collection were transferred to the current platform. Based on the results of the internal and external tests the platform was updated and is now available to the public worldwide.

Three mayor pathways were explored to collect data: (1) manual in-house input into Excel which could be expanded

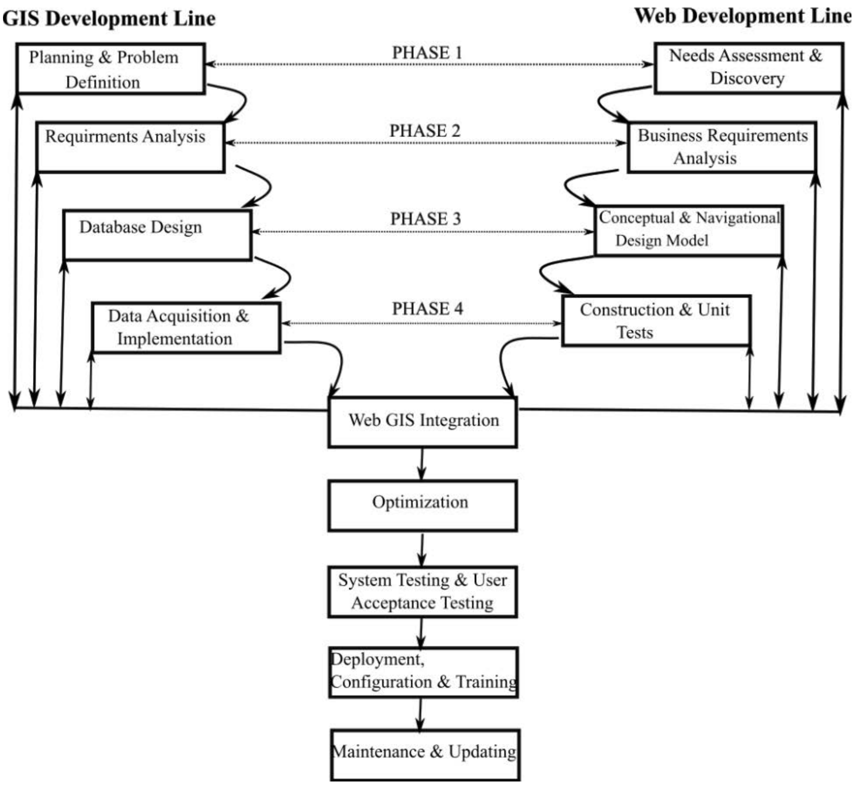

Fig. 1. Y-model WebGIS development methodology by Ananda et al. [15].

to external if needed; (2) the development of a semi-automated retrieval system of a limited sub-set of data items through R; (3) a template for the collection of CW information to facilitate data collection from the data providers and users. With this template users are able to upload directly the data to the platform. Limited attempts have been made to explore semi-automated transfers of data from existing databases. Another way of loading data into the platform is currently being developed in the form of importing multiple records through Excel formats. For now, CW data comes mostly from peer-reviewed journal articles or existing databases, but also some users have uploaded directly the data.

CWKP database is mainly grouped in three dimensions: (1) site-related information; (2) system-related information; (3) cell-related information and other information. Currently the database includes 14 tables and 134 parameters for each system. The water parameters take into account the water quality in the inflow, outflow and removal efficiencies. Functionality for data export was also developed. It is a tab on the page with a dynamic map, where the data can be downloaded in excel format.

Wetland specific data are visualized through two main mechanisms: an interactive map feature and a statistical computation tool. Maps and statistics display data dynamically, taking into account the filters that users can customize. The platform has dynamic maps showing the CWs uploaded worldwide with the respective information and can also be filtered based on different parameters that the user desires. Statistics are also displayed in the form of graphs which also can be downloaded. The platform contains important training material as well as various guidelines for CWs. The platform has English and Spanish versions. The users can contact each other through the messaging section. All these features make this platform interactive and easy to use for different users.

2. Methods

The goal of the article is to analyze the data stored in the CWKP platform, described in the previous section, and to assess how it can be used to support the CW design, and generally strengthen the practical capabilities of informed and advanced planning of these NBS and their application for the development of sustainable sanitation, especially in developing countries. To realize this goal, the statistical analyzes were conducted to assess how the type of CW and selected parameters of the wastewater treatment process affect the removal efficiency of wastewater treatment with CWs. The analyzes were carried out for data for CWs with (1) free water surface (FWS); (2) horizontal flow (HF) and (3) vertical flow (VF). Data records where type of CWs were combined or/and an additional wastewater treatment process was employed (such as aeration or disinfection) was omitted. Finally, 13 records for FWS CWs, 69 records for HF and 40 records for VF were taken for analysis. Using the ANOVA analysis of variance, it was evaluated whether the removal efficiency of chemical oxygen demand (COD), biochemical oxygen demand (BOD), total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS) and *Escherichia coli* bacteria differed statistically significantly between different types of CWs. The consistency of the distribution of the examined variables with the normal distribution was evaluated using the Shapiro–Wilk test, and the homogeneity of variance in the groups using the Bartlett test. The significance level was set to 0.05 ($\alpha = 0.05$). In addition, for the selected types of CWs, the Pearson coefficient (r) was used to evaluate how the hydraulic loading, temperature and age of CW affect the efficiency of removing individual indicators. All statistical analyzes were performed in R (ver. 4.1.0) with RStudio (ver. 1.4.1717).

3. Results and discussion

3.1. Influence of CW type on the treatment efficiency

Table 1 shows the average quality parameters of raw and treated wastewater for each analyzed type of CW. Fig. 2 shows the effect of CW type on the removal efficiency of individual analyzed parameters.

The average COD removal efficiency by the considered types of CWs was very similar and amounted to 78%, 73% and 74%, respectively for the FWS, HF and VF CWs. These results did not differ statistically. The lowest COD removal efficiency was observed in the case of VF CWs (17%). While the minimum recorded COD removal efficiency was 30% for HF CWs, and 55% for FWS CWs. The highest recorded COD removal efficiency was 98% for the FWS CWs. The maximum efficiency of removing this parameter for other types of CWs was 97% for HF and 95% for VF.

No statistical differences were also observed between the effectiveness of BOD removal by analyzed types of CWs, however, in the case of this parameter, the most effective were VF and FWS CWs, for which the effectiveness of BOD removal was 85% and 82%, respectively. HF CWs removed BOD with a lower average efficiency of 72%. For this type of CW, the lowest (of all results) BOD removal efficiency was also observed (less than 18%). For FWS CWs, the minimum BOD removal efficiency was 56%, and for VF – 61%. The maximum BOD removal efficiencies for all types of CWs were very high and amounted to 98% for FWS, 99% for VF and almost 100% (99.5) for HF.

The average efficiency of TN removal by individual types of CWs did not differ statistically and amounted to 51% for VF, 54% for HF and 65% for FWS. The lowest observed TN removal efficiency was recorded in the case of VF CW (5%). The minimum efficiency of TN removal by other types of CWs was 23% for HF and 47% for FWS. The maximum efficiency of TN removal by individual types of CWs was different and amounted to 72% for VF, 83% for FWS and 94% for HF.

The average efficiency of TP removal by analyzed types of CWs differed (45% for FWS, 51% for HF and 68% for VF), although these differences were not statistically significant. In the case of HF CWs, the lowest TP removal efficiency was observed among all the analyzed results (3%). For the remaining CW types, the minimum TP removal efficiencies were 22% and 25%, respectively for FWS and VF. The maximum efficiency of TP removal by individual types of CWs was high and amounted to 95% for VF, 97% for HF and 100% for FWS CWs.

TSS was removed best in the case of FWS CWs. For this CW type, the average removal efficiency of this parameter was 93%. The minimum efficiency of TSS removal for FWS CWs was also high (78%), while the maximum was 100%. The remaining types of CWs removed TSS with a statistically insignificant lower efficiency. For HF CWs the average TSS removal efficiency was 71%, and for VF – 72%. In the case of HF CWs, the minimum efficiency of TSS removal was 19% (the lowest among all), while the maximum was 96%. In the case of VF, these efficiencies were 28% and 91%, respectively.

Similarly, to TSS, *E. coli* bacteria was removed with the highest efficiency by the FWS CWs (97%). The minimum efficiency of *E. coli* removal by this type of CW was also very high (94%), while the maximum was 100%. *E. coli* removal

Table 1
Quality of raw and treated wastewater for analyzed types of constructed wetlands

Parameter	Average concentration (range)					
	FWS		HF		VF	
	inflow	outflow	inflow	outflow	inflow	outflow
COD, mg·O_2/L	4,019 (85–20,000)	156 (20–400)	665 (84–4,421)	247 (18–2,582)	205 (81–441)	53 (10–159)
BOD, mg·O_2/L	2,955 (23–15,000)	83 (2–200)	332 (5–2,167)	131 (1–1,391)	154 (25–300)	14 (1–49)
TN, mg/L	8.4 (5.2–11.6)	0.9 (0.9–0.9)	148.8 (28.0–294.3)	46.9 (6.3–100.5)	70.2 (5.2–99.8)	28.1 (2.1–50.4)
TP, mg/L	0.21 (0.17–0.25)	0.09 (0.01–0.17)	21.60 (3.50–60.00)	8.31 (0.37–44.10)	15.00 (2.50–29.52)	3.82 (0.30–8.60)
TSS, mg/L	6,795 (384–10,000)	150 (100–200)	407 (12–1,408)	122 (1–558)	87 (23–190)	28 (3–87)
E. coli, CFU/100 mL	n.a.*	n.a.*	$2.2 \cdot 10^6$ ($1.1 \cdot 10^3 – 7.9 \cdot 10^6$)	$1.8 \cdot 10^4$ ($1.6 \cdot 10^1 – 6.3 \cdot 10^4$)	$2.9 \cdot 10^6$ ($5 \cdot 10^0 – 7.0 \cdot 10^6$)	$6.7 \cdot 10^5$ ($4 \cdot 10^0 – 3.3 \cdot 10^6$)

*For FWS CWs only efficiencies were available in CWKP.

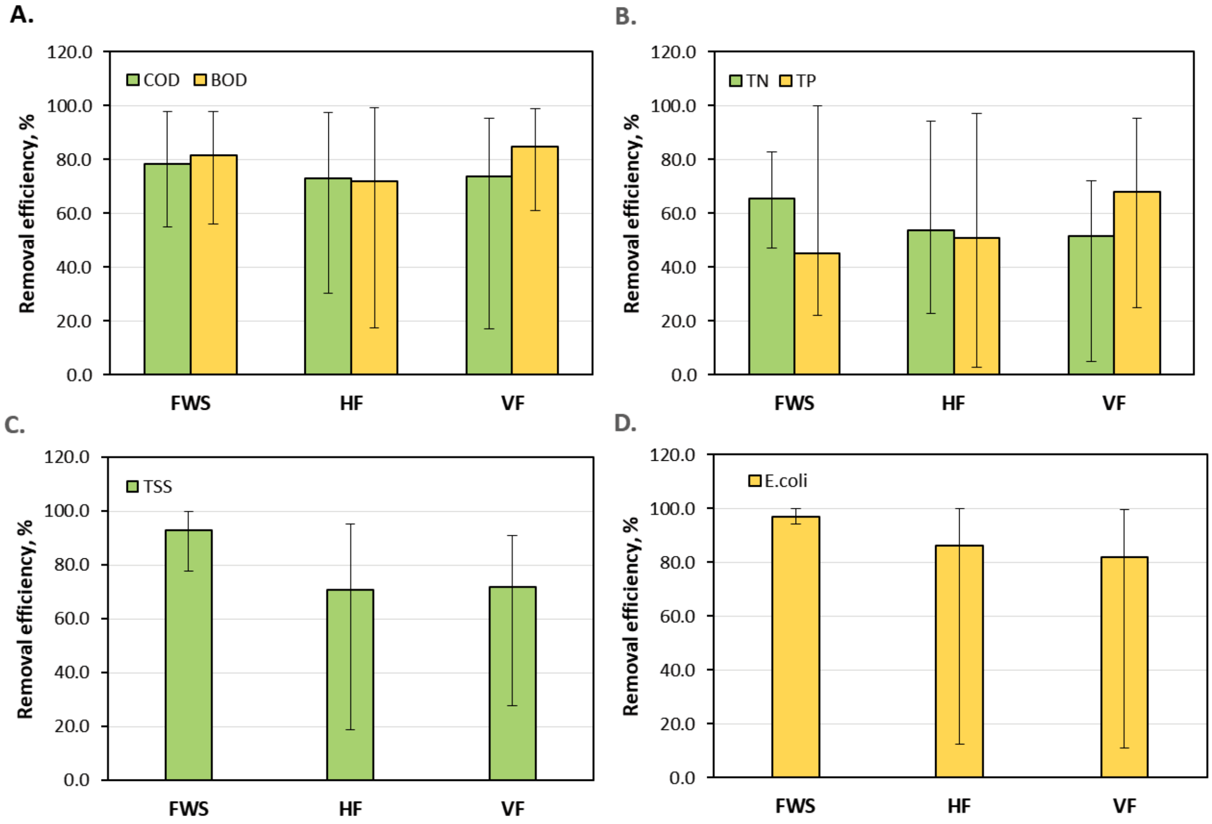

Fig. 2. Influence of the analyzed types of constructed wetlands on the removal efficiency of: chemical oxygen demand and biochemical oxygen demand (A), total nitrogen and total phosphorus (B), total suspended solids (C) and *Escherichia coli* (D).

by other types of CWs was statistically insignificantly lower and amounted to 86% for HF and 82% for VF. For these types of CWs, greater differences between the minimum and maximum efficiency of *E. coli* removal were observed. For HF, the minimum efficiency of *E. coli* removal was less than 13%, and the maximum was 100%. In the case of VF, the minimum and maximum efficiency of *E. coli* bacteria removal was 11% and slightly less than 100%, respectively.

3.2. Influence of treatment parameters on the efficiency of pollutant removal

Fig. 3 shows the influence of the hydraulic loading, temperature and CW age on removal efficiency of individual analyzed parameters, while Table 2 summarizes the Pearson correlation coefficients between the parameters of the treatment process and the removal efficiency of the wastewater quality parameters.

Taking into account the data from all types of CWs, the COD removal efficiency strongly depended on the hydraulic loading rate ($r = -0.61$), slightly positively on the temperature (0.12) and slightly negatively on the age (–0.07). Analyzing the influence of individual types of CWs, strong negative correlations were observed between the effectiveness of COD removal and the hydraulic loading rate for HF (–0.66) and VF (–0.70) and a moderate negative correlation for FWS (–0.36). Temperature strongly positively correlated for FWS (0.61) and moderately negatively correlated with VF (–0.33), while age correlated strongly positively for FWS (0.55), moderately negatively for HF (–0.42) and moderately positively for VF (0.32). The correlations between the BOD removal efficiency and the individual technical parameters of CWs for the results from all types of CWs were weak and amounted to 0.08 for the hydraulic loading rate, 0.05 for temperature and –0.16 for age. Taking into account the correlations for individual types of CWs, the hydraulic loading rate was correlated moderately negatively for FWS (–0.49), slightly negatively for HF (–0.07) and moderately positive for VF (0.33); temperature strongly positive for FWS (0.94), strongly negative for HF (–0.52) and moderately positive for VF (0.43); age was moderately negative for HF (–0.25), weak correlations were observed for the remaining types of CWs.

Taking into account the results from all types of CWs, a moderate negative correlation was found between the hydraulic loading rate and the removal effectiveness of TN (–0.34) and TP (–0.27). In the case of temperature, these correlations were positive and amounted to 0.13 and 0.48 for TN and TP, respectively. In the case of CW age, a weak negative correlation was observed for TN (–0.16) and a moderate negative correlation for TN (–0.42). When studying the correlations for the analyzed types of CWs, the efficiency of TN removal was slightly negatively correlated in individual groups – the values of Pearson's coefficients were –1.00 for FWS, –0.46 for HF and –0.89 for VF. In the case of temperature, a strong positive correlation was observed with

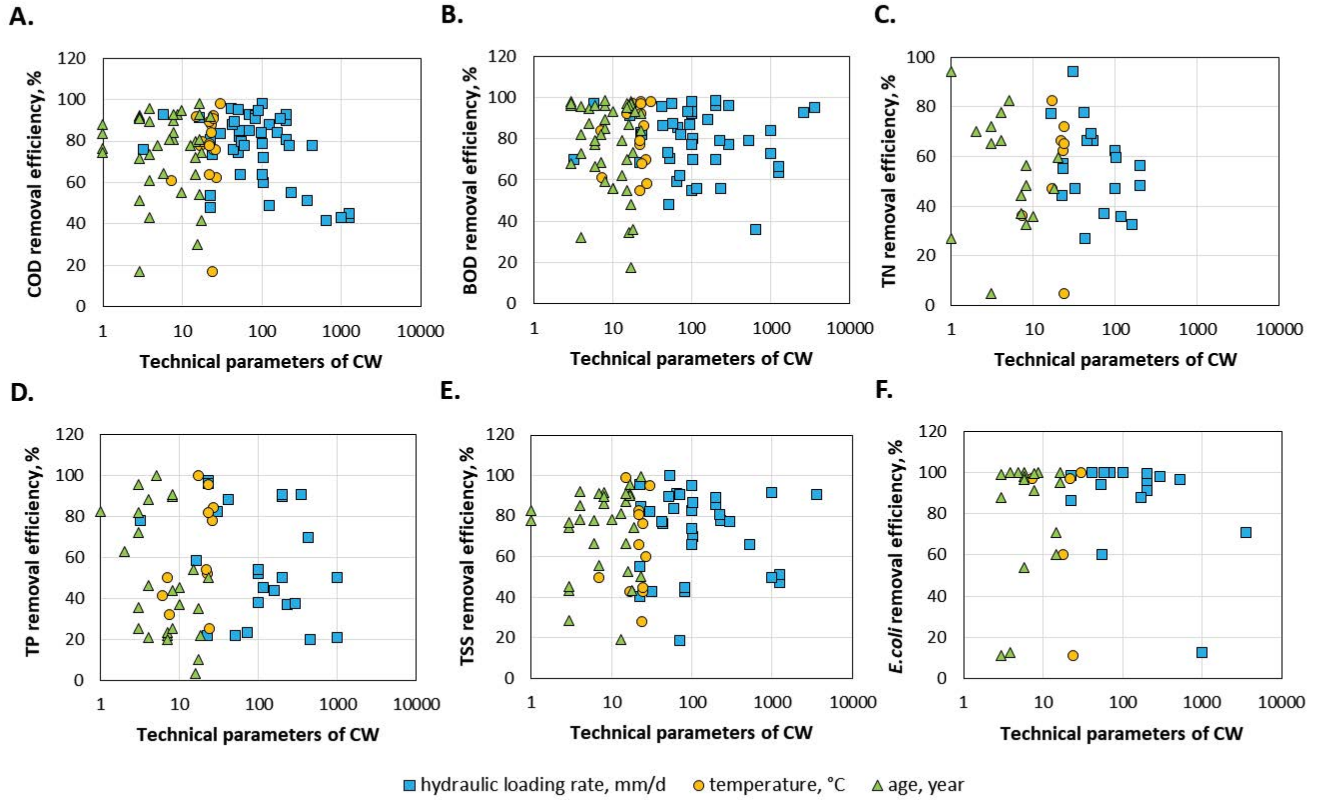

Fig. 3. Influence of hydraulic loading, temperature and age on removal efficiency of: chemical oxygen demand (A), biochemical oxygen demand (B), total nitrogen (C), total phosphorus (D), total suspended solids (E) and *Escherichia coli* (F).

Table 2
Pearson correlation coefficients between the treatment process parameters and the removal efficiency of the analyzed parameters of wastewater quality

	Hydraulic loading rate				Temperature				Age			
	All	FWS	HF	VF	All	FWS	HF	VF	All	FWS	HF	VF
COD	–0.61	–0.36	–0.66	–0.70	0.12	0.61	–0.19	–0.33	–0.07	0.55	–0.42	0.32
BOD	0.08	–0.49	–0.07	0.33	0.05	0.94	–0.52	0.43	–0.16	0.19	–0.25	–0.03
TN	–0.34	–1.00	–0.46	–0.89	0.13	n.d.*	0.92	0.16	–0.16	n.d.*	–0.41	0.20
TP	–0.27	0.67	–0.49	–0.55	0.48	0.97	1.00	0.25	–0.42	–0.89	–0.53	–0.09
TSS	0.02	–1.00	–0.13	0.15	0.12	–1.00	0.17	0.01	0.08	0.96	–0.12	0.12
E. coli	–0.39	1.00	–0.85	–0.90	–0.15	n.d.*	n.d.*	–0.58	0.18	n.d.*	0.06	0.14

*n.d. – not enough data

the efficiency of TN removal for HF, while for age, a moderate negative correlation was observed for HF (–0.41) and a moderate positive correlation for VF (0.20). In the case of a correlation between the effectiveness of TP removal and the hydraulic loading rate, a strong positive correlation was observed for FWS (0.67), a strong negative for VF (–0.55) and a moderate negative for HF (–0.49). Temperature had a positive impact on TP removal for all types of CWs – Pearson's coefficients were 0.97, 1.00 and 0.25 for FWS, HF and VF, respectively, while the age had a strong negative impact (–0.89 for FWS and –0.53 for HF). In the case of TSS, taking into account all the results totally, the removal efficiency of this parameter was poorly dependent on the hydraulic loading rate, temperature and age. Only in the case of FWS, strong relationships were found between the effectiveness of TSS removal and the hydraulic loading rate (–1.00), temperature (–1.00) and age (0.96). For the remaining types of CWs, the relationship between the TSS removal efficiency and technical parameters was weak. There were relatively few results of the content of *E. coli* bacteria in CWKP database. However, the obtained results show that the removal of this type of bacteria is moderately negatively dependent on the hydraulic loading rate (–0.39), slightly negatively on the temperature (–0.15) and slightly positively on the age (0.18). The effectiveness of *E. coli* removal depended strongly on the hydraulic loading rate for FWS (1.00) and strongly negatively for HF (–0.85) and VF (–0.90). A negative moderate correlation was also observed between the efficiency of removing these bacteria and the temperature for VF (–0.58). Due to the fact that the main mechanism for removing pollutants in the constructed wetlands is the activity of microorganisms and the biological decomposition of pollutants, the efficiency of pollutant removal is higher for lower hydraulic loading rates [2,9]. These processes are favored by higher temperatures, therefore the efficiency of pollutant removal increases with increasing temperature, and decreases at low temperatures, for example in winter in Europe [1,14]. The age of the constructed wetland, and thus the development of appropriate microflora, also positively affects the efficiency of removing organic matter from wastewater in this type of facility [5,3]. The obtained correlations between the pollutants COD, BOD, TN, TP and treatment process parameters, such as hydraulic loading rate and temperature, generally confirmed these relationships. Due to the scarcity of data, satisfactory results have not been obtained for *E. coli*. It is also difficult to explain that the analyzes performed on CWKP did not confirm the positive effect of the age of the constructed wetlands on improving the removal efficiency of COD, BOD, TN and TP. However, this may be caused on the one hand by the still limited number of records in CWKP, on the other hand by a large variety of technical parameters, but especially geographical and meteorological ones. Undoubtedly, further development of the CWKP database will allow for in-depth and more extensive analyses.

4. Conclusions

In the article the potential of online tools to support the design and popularization of constructed wetlands were analyzed. To realize this goal the data base of internet knowledge platform CWKP (Constructed Wetland Knowledge Platform) were described and analyzed, and influence of key parameters and features of constructed wetlands on their performance were evaluated with the statistical techniques. The analyses of CWKP resources showed:

- constructed wetlands of all analyzed types remove efficiently COD (73%–78%);
- BOD is removed more efficiently by analyzed vertical flow constructed wetlands (85%) and free water surface constructed wetlands 82%; horizontal flow constructed wetlands remove BOD with a lower efficiency (72%);
- the average removal efficiency for total nitrogen was 51% for VF, 54% for HF and 65% for FWS and for total phosphorous: 45% for FWS, 51% for HF and 68% for VF (however the single objects reached the efficiency on a level of 95% for VF, 97% for HF and 100% for FWS);
- the highest average efficiency of TSS removal was observed for FWS (93%), the lower effects were observed for VF (72%) and HF (71%);
- Generally, *E. coli* bacteria was removed especially efficiently by FWS (97%), for other types the observed effect was not bad either (86% for HF and 82% for VF);

Concluding, the analyzes carried out in the article have shown that the online tools, as CWKP, can provide significant support in the selection of appropriate design solutions, as well as professional design of wetlands. Thus, such a platform has a significant potential for popularizing wetlands and their practical application in various environmental, climatic, technical and social conditions; and it also the real support for designers, decision-makers and other professional searching for innovative and sustainable solutions for wastewater treatment sector.

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