Contribution of Constructed Wetlands for Reclaimed Water Production: A Review

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Abstract. Freshwater scarcity is a growing threat to sustainable development, which can be mitigated by adequate management of water resources. Agriculture and related activities consist in the main use of freshwater, but several other human activities present relevant contributions. Because most of the water uses imply the generation of resultant wastewater, the production and use of reclaimed water by appropriate technologies can be part of the solution to that issue. Considering that the use of constructed wetlands (CWs) can be a relevant contribution to the production of reclaimed water, as an eco-friendly alternative to costly advanced water treatment technologies, this work is a review of the last decade of literature on the use of CWs to produce reclaimed water. The results point to a usual focus on the production of reclaimed water for agriculture or urban spaces irrigation. In order to potentiate a broader application of CWs, some directions of future research and use of this green technology are proposed.

1. Introduction

Freshwater scarcity is a growing threat to sustainable development [1–3]. To cope with this issue, the United Nations identified the objective to ensure water resources management in terms of quantity and quality of water supply and sanitation as the sixth goal of the sustainable development goals [4,5]. Agriculture and related activities consist in the main use of freshwater [6,7], but several other human activities present relevant contributions. Most of the water uses imply the generation of resultant wastewater. Although a significant part of the generated wastewater is not yet subject to any kind of treatment [8], the production of reclaimed water by appropriate technologies can be a relevant contribution to water resources protection and valorisation [9–11].

Reclaimed water consists of wastewater treated by adequate processes that ensure water quality and absence of risk, qualifying the water to be used for some purpose, replacing or decreasing the consumption of freshwater [12,13]. Wastewaters may be generated by different sources, which may be mixed, originating a complex matrix of water pollutants. In general, there are three main types of wastewater: domestic, urban, and industrial [14]. Other minor, but not less relevant types, may also be considered, such as greywater, stormwater, and runoff water. Domestic wastewater is produced in households and similar human urban spaces (Hotels, Restaurants, Public and commercial toilets, and restrooms). It consists of a mixture of blackwater, from toilets, with greywater, from washing and cleaning, bathing, and kitchen. Municipal or urban wastewater is a mixture of domestic with industrial wastewaters. Stormwater includes rainwater, and snow and ice melting, which may cause runoff waters that may include leached compounds originated by the interaction of the water with the soil, landfills, or pavements [15].

The wastewater treatment technologies are diverse, strongly dependent on the wastewater composition and flow rate, and the end-use aim or disposal location. Usually, wastewater treatments are organized in three main stages: primary, secondary, and tertiary or advanced [14]. After the primary stage, and eventual preliminary treatments, the wastewater should be free of large objects and part of the suspended solids, greases, and other organic matter. The aim of the second stage consists of the removal of biodegradable organic matter and may include disinfection. Tertiary, or advanced treatments, aims to remove residual suspended solids and nutrients, and usually include disinfection.

The end uses of reclaimed water may also be diverse and will be described in section 2. Although the quality of reclaimed water for some end uses may be attained with secondary treatments, main reclaimed water end uses require advanced treatments, which may include disinfection [16]. Examples of advanced treatments are additional settling or filtration, coagulation-flocculation, desalination, maturation lagoons, and constructed wetlands (CWs). CWs consist of an eco-efficient and green technology that can contribute to lower the costs of wastewater treatment and potentiate the dissemination of reclaimed water production and reuse [17,18]. Although CWs are usually targeted to treat secondary wastewaters, they can be used to replace secondary treatment and even the primary treatment [19,20]. This option, under a controlled design and operation, can be a solution for decentralized wastewater treatment systems, in which the wastewater is treated and reused closer or at the point of its generation [21], despite the relevance of using CWs in centralized municipal or industrial plants.

There are available some previous reviews on reclaimed water production by CWs. Tao et al. [22] proposed a set of design orientations for using CWs to produce reclaimed water, based on the available data from 31 full-scale CWs. Most of the CWs reported in that work received secondary treated wastewater, river water, or stormwater, while 11 received primary treated wastewater, with the majority producing reclaimed water for non-potable uses. Lavrnić and Mancini [23] analysed the data available in the literature for 29 pilot and full-scale CWs in four Southern European countries and made a comparison of the reported composition of the treated wastewater with the country-existent regulations for reclaimed water reuse in agriculture in 2016. They observed that several treatment plants can provide sufficient water quality for irrigation, but there is a lack of data on some relevant parameters, namely the microbiologic indicators. Almuktar et al. [24] reviewed the CWs characteristics, designs, and efficiencies in wastewater treatment considering the hypothetical reuse of the treated wastewater in agriculture. Shingare et al. [25] made a review on the CWs' capacity to remove pathogens from the wastewater, claiming that is a critical and understudied factor to enable reclaimed water reuse regarding risks of contamination.

The work of Nan et al. [26] focused on the review of published work describing the use of CWs to treat domestic wastewater and consequent evaluation of the potential for water reuse in agriculture. These authors compared the reported quality parameters of the treated water with the current EU criteria to use the reclaimed water for irrigation purposes. They observed that for most CWs systems there is a need for additional treatment steps, and, particularly, the application of disinfection measures.

The present work is intended to complement and extend the work of Tao et al. [22], by including published work on studies carried out with pilot-scale CWs in the last decade, and full-scale data not covered by the referred previous review. The data gathered was organized according to the wastewater and CW types, end uses, water quality analysis and experiments carried out to validate the end-use quality criteria.

2. Methods

The review work of Tao et al. [22] that refers to 31 examples of full-scale CWs applied to reclaimed water production was used as starting point. Then, a search in Scopus database was conducted to complete the data set to include pilot-scale and other examples not covered by the referred work. The contents of the extracted documents were evaluated for the focus on the end uses of the reclaimed water produced by CWs. The documents published from 2010 onwards and providing the characteristics of the CWs, wastewater type, analysis performed and water end-use were selected, and then organized according to an adaptation of the end uses of reclaimed water classification following Chen et al. [9] and the main types of wastewater.

3. Results

3.1. Application of CWs by wastewater source and end uses

Figure 1 shows the density of the selected published works over a two-dimensional matrix. One dimension is the end use of the reclaimed water, and the other dimension is the source of the treated wastewater: Domestic, Urban, Industrial, and Others, like greywater and stormwater.

The end uses are organized in: (i) Potable Uses - direct or indirect; (ii), Non-potable Uses - irrigation of animal feeding, food crops, non-food plantations or woodlands, aquaculture production, and urban and residential uses that may include green spaces irrigation, urban lakes, ponds, fountains and recreative spaces, cleaning of urban areas and roads, fire protection, air conditioning, toilet flushing, and washing of cars and clothes, among other urban uses; (iii) Groundwater and Environment - groundwater replenishment, streams recovery and augmentation, seawater intrusion barrier; (iv) and Industrial Uses - such as process water, cooling water, boiler make-up water, and washing of spaces and equipment. Most works focus on the use of reclaimed water for non-potable uses, mainly for irrigation purposes. Table 1 contains references to published work on using reclaimed water for irrigation, which is not covered by the review of Tao and co-workers. The table data includes the type of CW, post-treatment if applied, and the relevant water analysis performed. CWs can be designed in a variety of types, configurations, and combinations [20]. Three main types are common and classified according to the flow arrangement of the water under treatment: subsurface vertical flow CWs, SSVF, abbreviated as VF; subsurface horizontal flow CWs, SSHF, abbreviated as HF; and free surface flow CWs, FSF. When not indicated by the authors, domestic wastewater was considered as urban, and irrigation end-use was classified as for agriculture purposes.

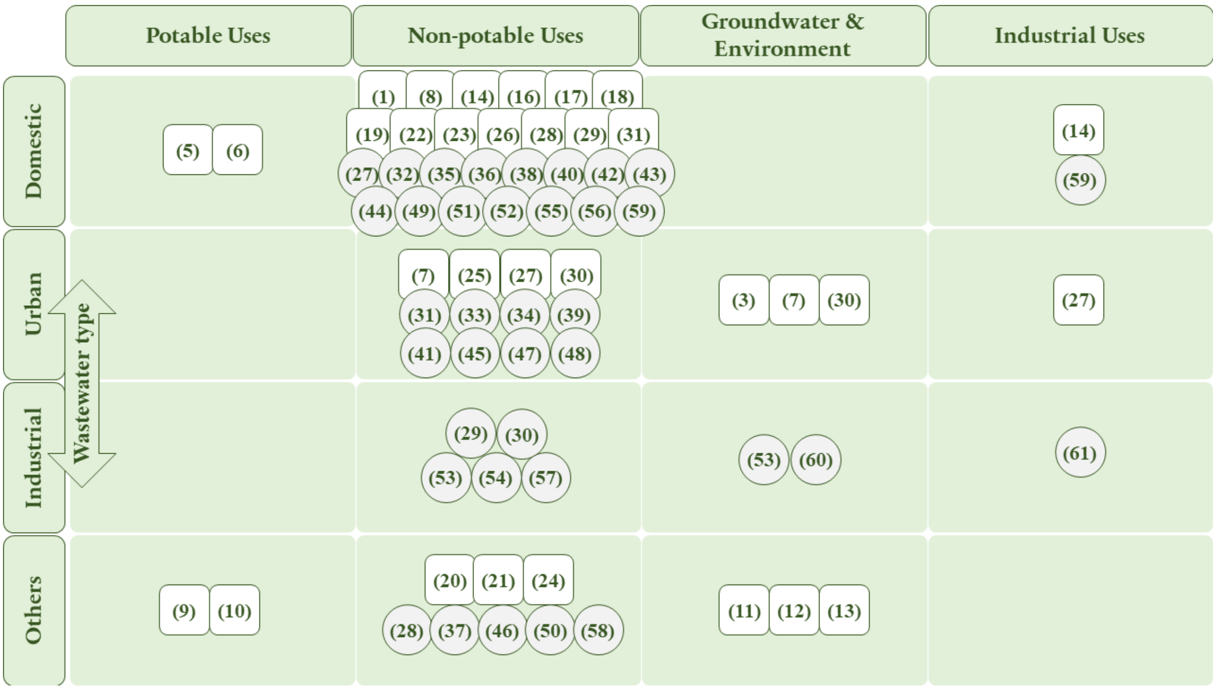

Figure 1. Distribution of the works referred by Tao and co-workers (squares) and the retrieved published works on producing reclaimed water by constructed wetlands in the last decade (circles). The numbers inside squares refer to the works listed in Table 2 of the Tao et al. review [22]. The numbers inside the circles coincide with the reference list of the present work.

From Table 1 it is observed that 70% of the identified works propose the use of the reclaimed water for irrigation in agriculture, but most of this end-use applicability is based on theoretical comparison of the treated water quality with the current legislation (identified with T in the table).

Table 1. – Published work on using reclaimed water produced by CWs for irrigation.

Type of wastewater	Type of CW	Post-treatment	Analysis	End-use/test	Ref.
Raw domestic	VF + HF	-	Nut, EC, TSS, SAR, M, O, Mic	Agr/T!	[27]
Artificial raw greywater	VF	-	Nut, TSS, pH, SAR, EC, O, M, Mic	Agr/P!	[28]
Industrial (Pig farm)	VF	-	Mic	Agr/T!	[29]
Industrial (Textile)	HF	-	Nut, TSS, pH, DO, O, M	Agr/P!	[30]
Primary urban	VF	-	Nut, TDS, TSS, O, Mic	Agr/T!	[31]
Secondary domestic	HF	-	Nut, TSS, pH, DO, EC, O, Mic	Urb/T	[32]
Secondary urban	VF + HF + FSF	-	Nut, TDS, TSS, pH, DO, EC, Mic	Agr/T	[33]
Secondary urban	HF	Pond + US + UV	Nut, TSS, O, Mic	Agr/T!	[34]
Secondary domestic	HF	-	Nut, TSS, Mic	Agr/T!	[35]
Primary domestic	HF + VF combinations	-	Nut, TSS, Mic	Urb/T!	[36]
A mix of greywater and wastewater from laboratories	HF + VF combinations	Ponds	Nut, TSS, pH, DO, EC, Mic	Agr/T	[37]
Secondary domestic	HF + VF	-	Nut, TSS, pH, DO, EC, O, Mic	Urb/T!	[38]
Primary urban	HF + VF combinations	-	Nut, TSS, pH, DO, EC, Mic	Agr/T	[39]
Secondary domestic	HF	-	Nut, TSS, pH, DO, EC, SAR, M, O, Mic	Agr/P	[40]
Secondary urban	HF + VF	-	Nut, TSS, pH, Mic	Urb/T!	[41]
Primary domestic	HF	-	Nut, TSS, pH, DO, EC, SAR, M, O, Mic	Agr/T	[42]
Secondary domestic	VF	-	Nut, TSS, pH, DO, EC, Mic	Agr/P!	[43]
Primary domestic	HF	-	Nut, TSS, pH, DO, EC, O, Mic	Agr/T	[44]
Secondary urban	HF	-	Nut, TSS, pH, DO, EC, M, O, Mic	Urb/P	[45]
Raw greywater	HF	-	Nut, TSS, pH, O, Mic	Urb/T!	[46]
Primary urban	VF	Vegetation ponds	Nut, TDS, pH, EC, M, O	Agr/T	[47]
Secondary urban	HF	Filters + Pond or UV	Nut, TSS, pH, EC, SAR, O, Mic	Agr/P	[48]
Raw domestic	HF + VF	-	Nut, TSS, O, Mic	Agr/T!	[49]
A mix of stormwater and primary domestic	HF + FSF	-	Nut, TSS, pH, DO, EC, M, O, Mic	Urb/T	[50]
Secondary domestic	Hybrid + VF	Ozonation	Nut, TDS, pH, EC, O, Mic	Urb/P	[51]
Secondary domestic	HF	Chlorination or UV	Nut, TSS, pH, EC, O, Mic	Urb/P!	[52]
Industrial (Reverse Osmosis concentrate)	HF/VF	-	Nut, TDS, pH, EC	Urb/T	[53]
Industrial (Pig farm)	VF	-	Nut, M	Agr/T	[54]
Primary domestic	VF	Natural UV	Nut, TDS, TSS, pH, DO, EC, O, Mic	Agr/T	[55]
Primary domestic	VF + HF	-	Nut, TSS, pH, EC, Mic	Agr/T	[56]
Industrial (Winery)	VF + HF + FSF	-	Nut, TSS, pH, EC, Mic	Agr/T!	[57]
Greywater	VF	Filter + Chlorination	Nut, TSS, pH, DO, EC, O, Mic	Urb/T!	[58]
Secondary domestic	HF	-	Nut, TSS, pH, DO, EC, M, O, Mic	Urb/P	[59]

Type of CW: HF= Subsurface horizontal flow; VF= Subsurface vertical flow; FSF= Free surface flow; "+"= set of serial or parallel arrangements; "/"= Alternative modes. Type of post-treatment: UV= Ultraviolet; US= Ultrasounds. Analysis: Nut= Nutrients, such as Total Nitrogen, Total Phosphorous, Chemical Oxygen Demand, Biochemical Oxygen Demand, or related analysis; TSS= Total Suspended Solids; TDS= Total Dissolved Solids; SAR= Sodium Absorption Ratio; EC= Electrical Conductivity; DO= Dissolved Oxygen; M= Metals; O= Other analysis; Mic= Microbiologic indicators. End-use/Test: Agr= Irrigation in agriculture; Urb= Irrigation in urban sites; T= Theoretical risk evaluation; P= Practical risk evaluation based on irrigation experiments; "!" Issues identified or abcense of risks not clearly demonstrated.

Only 23% of works attempted evaluating the effects of the reclaimed water by some kind of irrigation experiment (marked as P in the table). Using the theoretical or practical approaches, 48% of the works either identified some risk or had lacking data in the experiments that impeded the risk evaluation (references marked with ! in the end-use test). However, because the most commonly identified risks are related to the microbiological contents of the reclaimed water, disinfection is generally recommended as a solution.

3.2. Cases presenting lower research intensity

As can be seen in Figure 1, the most reported data refers to the use of reclaimed water for non-potable uses (near 77% of total cases), and almost all cases within non-potable uses report to irrigation purposes (more than 95%). Few recent works are focusing on the use of CWs to produce reclaimed water for applications other than non-potable uses in the last decade.

Xing et al. [60] describe a real-scale plant that combines oxidation and stabilizations ponds with free surface flow and subsurface flow CWs to treat papermaking wastewater after advanced treatment by a fluidized-bed Fenton reactor. The reclaimed water is used to restore the water quality of the Shuangji River, in China. In addition to the usual water quality parameters (Nutrients and dissolved oxygen), the dissolved organic matter was characterized, and in-vitro and in-vivo toxicity assays were carried out.

Besides using the reclaimed water for irrigation purposes, Chakraborti and Bays [53] also propose the use of the reclaimed water produced by a pilot-scale combined horizontal and vertical flow CW to feed coastal wetlands. The CW treats wastewater that consists in the concentrate stream of a Reverse Osmosis unit of a water treatment facility. The authors mention an ongoing study of a full-scale three-stage plant consisting of horizontal subsurface CWs, an up-flow vertical flow CW, and a free surface flow CW.

Pinho and Mateus [59] proposed the use of reclaimed water treated by a pilot-scale modular CW for combined irrigation and microalgae production. Although several works focused on the use of algae to treat and recover wastewater, there are no other examples of using reclaimed water produced by CWs. In this work, the microalgae cultivation serves as a complement to reclaimed water valorisation during rainy and cold seasons when the need for irrigation is lower. In addition to demonstrating the absence of toxic effects of the reclaimed water on the microalgae growth, additional toxicity tests were carried out with ornamental plants.

Riggio et al. [61] studied the production of reclaimed water by vertical flow and horizontal pilot-scale CWs. The source of the wastewater is a WWTP treating effluent from an automotive parts industrial plant. The CWs were tested to produce reclaimed water to be returned to the industrial process, diminishing the use of water from wells. Because the electrical conductivity, alkalinity, and calcium content of the reclaimed water did not meet the requirements, the authors concluded that CWs could fit the proposed objectives but require further research on adequate filling media.

4. Perspectives for future research and applications

Based on the potential uses of reclaimed water, and considering the results presented in Figure 1, there are opportunities to explore the CWs' capabilities to contribute to a broader set of applications. Potable and Industrial uses are the less explored in the reviewed literature.

Although the main reported applications of CWs focus on the production of reclaimed water for irrigation purposes, it should be mentioned that the quality criteria attained may be enough for other applications, particularly in the industrial end uses, such as the power sector [62]. The research reviewed, and presented in Table 1, points to the need to improve future work to validate the risks of using reclaimed water.

Some potential uses seem to be less explored, such as the use of reclaimed water for firefighting, and industrial applications. Although the standards for the use in potable applications are stringent, this end-use may represent a relevant market to foster the production of reclaimed water, in which the contribution of CWs can be considered [63]. There are also few reports on the use of CWs to reclaim

greywater and stormwater, which can be a potential use of CWs since this technology works well with low-strength wastewaters and is very resilient to non-conventional pollutants [20].
A particular strength of CWs, the multiple modes of design and operation and the consequent adaptability to different wastewaters and reclaimed water applications, is also a barrier to the spread of this technology. As an example of this barrier, all CWs described in this review have different particularities of design and operation. A shorter set of design and operation schemes may foster the spread of the technology, by presenting a set of fewer complex scenarios to the stakeholders. Similarly, the regulations on the production and use of reclaimed water are still diverse, as observed in the reviewed works. The standardization of regulations can also facilitate the dissemination of CWs technology in the water management framework. Moreover, the current efforts to overcome institutional, social, and economic barriers to the use of reclaimed water [64] are an opportunity to be taken into account to leverage the role of CWs.

5. Conclusions
Reclaiming wastewater has a special role in the mitigation of the growing water scarcity threat. Among the available technologies that can contribute to attaining a proper quality of reclaimed water, CWs may have a special role due to their eco-efficiency, low-cost implementation and operation, flexibility, and link to sustainable development and circular economy. Through a review of published work on the production of reclaimed water by CWs in the last decade, combined with a recent review on examples of full-scale reclaiming plants based on CWs, it was observed that most research and fieldwork focus on the use for irrigation or environmental applications, and, mainly, in reclaiming domestic and urban wastewaters. Using other types of wastewater, such as greywater, stormwater, and industrial wastewaters may represent an opportunity to explore CWs implementation. There is still also a need to focus the research on the treated water quality pertaining to these end uses, and a need to standardize reclaimed water regulations and CWs design and operation.

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