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The effectiveness of laboratory-scale hybrid constructed wetland wastewater treatment plant model in treating wastewater in the Tukad Badung River, Denpasar, Bali

Kadek Diana Harmayani[1*], I Gusti Agung Gede Wiranata Baskhara[1], Ni Made Pertiwi Jaya[1], Ida Ayu Rai Widhiawati[1], Masahiko Nagai[2], Daniel Rizal Mahendra[1], Debora Sofia Fransiska Hutagalung[1], Nyoman Dewi Supriyani[1], Putu Agus Ary Wiratama[1], Kadek Laksmi Satyawati[1]

[1] Program Study of Environmental Engineering, Faculty of Engineering, Udayana University, Bukit Jimbaran Campus, Badung, Bali, 80361, Indonesia
[2] Department of Center for Research and Application for Satellite Remote Sensing, School of Sciences and Technology for Innovation, University of Yamaguchi,Yamaguchi, 753-8511, Japan
* Corresponding author's e-mail: kdharmayani@unud.ac.id

ABSTRACT

The Tukad Badung River is polluted due to waste contamination from community activities. Community activities along the Tukad Badung basin produce considerable waste channeled into the river without processing. The Tukad Badung River water that flows downstream is collected to be used as a source of raw water for clean water at the Estuary Water Treatment Plant of PDAM Tirta Mangutama Badung Regency, therefore the water quality of the Tukad Badung River needs to be considered. Constructed wetlands (CW) are wastewater treatment systems that can be used to reduce pollutants entering Tukad Badung. This study aims to measure the efficiency of a terracing CW system in reducing the pollutant parameters BOD, COD, TSS, and ammonia. A lab-scale hybrid CW reactor test applied a terracing concept. It is a combination of free water surface (FWS) and subsurface (SSF) CW and was made from a plastic container that was 83.5 × 58.7 × 45 cm and filled with media gravel and sand as a substrate. The reactor utilized water jasmine (*Echinodorus palaefolius*) and dwarf papyrus (*Cyperus haspan*), with the planned hydraulic retention time (HRT) for FWS and SSF being two days and three days, respectively. The study results show the removal efficiency values for the BOD, COD, TSS, and ammonia parameters to be 93%, 82%, 96%, and 39%, respectively. The resulting efficiency in ammonia parameters is less than optimal; this is caused by minimal adaptation time, resulting in plant roots not being ready to provide sufficient oxygen supply for the nitrification process.

Keywords: constructed wetland, hybrid system, wastewater treatment, Tukad Badung.

INTRODUCTION

Water is an essential resource for life on Earth, and rivers are one source of clean water supply in everyday life. The increasing population has resulted in an increasing need for clean water. However, this is different from the current condition of water sources, as many water sources have experienced a decline in water quality due to exploitation by the surrounding areas through agricultural and economic activities and meeting daily needs (Hadisantoso et al., 2018; Haribowo et al., 2017; Zurita et al., 2006).

The 2009 Environmental Status of Bali Province states that ten rivers in Bali Province have experienced a decline in quality due to waste contamination. Tukad Badung is one of these rivers. The data on Status Lingkungan Hidup Provinsi Bali 2009 shows that the levels of TSS, BOD, COD and Ammonia in Tukad Badung are 2.689 mg/l, 4.3 mg/l, 20.59 mg/l, and 0.995 mg/l. The Tukad Badung River is a river that crosses the cities of Badung and Denpasar, which are densely populated areas. Intense community activities along Tukad Badung produce domestic waste, agriculture, livestock, and industrial activities such as tofu, tempeh, and screen printing (Balai Lingkungan Hidup Provinsi Bali, 2010). This waste continues to flow into river bodies without any prior processing, resulting in decreased river water quality (Rachmawardani et al., 2017). Harmayani et al. 2022, who claimed in their research that the Tukad Badung River was polluted, confirmed this once more. Parameters such as TSS, BOD, COD, and ammonia have passed quality standards upstream, middle stream, and downstream (Harmayani et al., 2023).

Tukad Badung River water that flows downstream is collected to be used as a raw water source for drinking water at the Muara Water Treatment Plant of PDAM Tirta Mangutama Badung so that the Tukad Badung River water quality factor needs to be considered. Research conducted by Harmayani et al. in 2022 shows that the average values of parameters such as TSS, BOD, COD and ammonia in the upstream, middle and downstream areas are 143 mg/l, 6.04 mg/l, 46 mg/l and 0.37 mg/l which exceed the quality standards class 1 river water based on PP no. 22 of 2021 (Harmayani et al., 2023).

Enhancing river water quality can be achieved by blocking or reducing the waste entering the river (Teknis et al., 2017). Wastewater processing can be performed at a wastewater treatment plant (WWTP). Waste processing in WWTP in the form of aerobic ponds, trickling filters, and rotating bio-contactors (RBC) has proven to be able to reduce pollutant parameters entering the river; however, building the WWTP requires quite a lot of costs, both for construction and operations (Faisal and Ali, 2017).

Constructed wetlands (CW) are manufactured wastewater treatment systems that imitate the structure of natural wetlands (Hammer, 1989). The four main components of CW are water, media, microbes, and vegetation, each of which has a role in reducing pollutants (Shelef et al., 2013). Pollutants are removed through physical mechanisms such as filtration or sedimentation and biochemical interactions such as microbial degradation (Shelef et al., 2013). Besides its lower implementation and operational costs in comparison to other treatment technologies, CW system can effectively and robustly process industrial and domestic wastewaters (Stefanakis and Tsihrintzis, 2012, Wu et al., 2015). In addition to reducing pollutants, this system can also reduce the organic load from wastewater and runoff (Belmont et al., 2006; Zurita et al., 2006), so CW can be used as a solution to reduce pollutants while improving the water quality of the Tukad Badung.

However, despite the advantages that CW offers both economically and environmentally, high pollutant loads and high surface area requirements are some of the things that can make this system difficult to implement (Horn et al., 2014). Therefore, the combination of various methods of treatment to maximize CW potential and reduce their limits is a topic that has gained increasing attention in recent years (Lutterbeck et al., 2018).

Based on the flow system, constructed wetlands are divided into surface flow systems, free water surface (FWS), and sub-surface flow systems or sub-surface flow (SSF). This study uses a hybrid concept of FWS and SSF-constructed wetlands. Authors of several studies have compared the performance of a hybrid CW to that of a single CW. For example, Audina and Rahmadiyanti (2019) said that processing waste with a hybrid system usually works better than with a single system (Audina and Rahmadyanti, 2019). Rito (2017), who discussed hybrid CW, mutually overcomes the weaknesses of the two CW systems used so that hybrid CW can obtain better efficiency in reducing pollutant parameters (Rito, 2017; Vymazal, 2013).

As reported by Audina and Rahmadiyanti (2019), hybrid-constructed wetlands are more effective in reducing COD and TSS pollution parameters. For example, CW hybrids have removal efficiency values of 83.16% and 98.51%, while single CW systems have 71.9% and 96% (Audina and Rahmadyanti, 2019). Additionally, according to Kraiem et al. (2019), hybrid CW has a slightly higher removal effectiveness for the TKN metric (total kjehdal nitrogen) than single CW, at 53% for hybrid and 48% for single CW (Kraiem et al., 2019). Therefore, hybrid CW has better removal efficiency compared to single CW, this occurs as a result of hybrid CW mutually overcomes the weaknesses of the two CW systems used so that hybrid CW can obtain better efficiency in reducing pollutant parameters (Rito, 2017; Vymazal, 2013).

Plants are an essential component of CW (Kalff, 2002). Plants grown in CW have several properties related to the processing process, so plants are an essential component of CW design (Brix, 1997). The plant in the FWS reactor is water jasmine (*Echinodorus palaefolius*), according to Prayitno (2013), which can reduce the load of organic and inorganic pollutants (Prayitno, 2013). In addition, it grows easily and quickly, so when used in constructed wetland systems, it can adapt quickly (Al Kholif et al., 2020). The SSF reactor uses papyrus dwarf (*Cyperus haspan*), which is one of the most productive wetland plants for bioremediation and can grow well in tropical climates (Akinbile et al., 2012; Matamoros et al., 2005).

Constructed wetlands have the advantages of lower costs, easy maintenance, longer installation sustainability, and more flexible location determination, and they can reduce pollutant levels by the same percentage as other processing systems (Rachmawardani et al., 2017; Stefanakis et al., 2014). This study aims to find out how well a laboratory-scale hybrid CW reactor treats water from the Tukad Badung River. The efficiency value will show how well CW works with the hybrid concept when treating water from the Tukad Badung River.

MATERIALS AND METHODS

Laboratorium-scale wetland reactor

Laboratory-scale wetland reactor testing was conducted in a greenhouse at the Faculty of Engineering, Udayana University, Jl. Bukit Campus, Jimbaran. The reactor is based on the terracing concept, combining FWS and SSF. Plastic containers filled with gravel and sand were used as substrates for the FWS and SSF reactors. It underwent cleaning before placing the gravel medium in the reactor. The sand and gravel in the reactor were arranged based on grain size and the media height is calculated based on research by Mayori (2022), Audina and Rahmadyanti (2019), and Mayori (2022). In the FWS reactor, gravel with a grain size of 3-5 cm was placed in the bottom layer with a medium thickness of 15 cm, followed by sand with a medium thickness of 10 cm. The SSF reactor used a split coral stone with a grain size of 3-5 cm in the bottom layer and a medium thickness of 10 cm. In the middle layer, use split coral stone with a grain size of 0.8–2 cm and a medium thickness of 5 cm, and sand in the top layer with a medium thickness of 10 cm.

The discharge supplied to the reactor was 60 L/day (0.000694444 L/s), according to the volume of the water container used. The hydraulic retention time (HRT) (td) was calculated using Equation (1). (Fauzi, 2016; Husnabilah and Tangahu, 2016):

$$v = Qinlet \times td \qquad (1)$$

The volume used for each reactor was 81 × 58 × 45 cm, according to the plastic container. Therefore, the calculation for HRT are presented below.

$$v = \text{Qinlet} \times \text{td}$$

$$81 \times 58 \times 45\ \text{cm} = 60\ \text{L/day} \times \text{td}$$

$$211{,}410\ \text{cm}^3 = 60\ \text{L/day} \times \text{td}$$

$$211{,}41\ \text{L} = 60\ \text{L/day} \times \text{td} \qquad q$$

$$3.52\ \text{day} = \text{td}$$

The retention time obtained from the calculation results was two days for the FWS reactor and three days for the SSF reactor; therefore, the total retention time for the CW hybrid was five days.

The reactor is combined using a 2.5 inch pipe. Each reactor is planted with different plants according to the type of CW used and the types of plants that can grow well in tropical climates (Akinbile et al., 2012). The plant used in the FWS reactor was water jasmine (*Echinodorus palaefolius*), and three water jasmine plants (*Echinodorus palaefolius*) were arranged in a cross-section with a distance of 25 cm between plants (Kartikawati, 2019). The SSF reactor was planted with eight dwarf papyrus (*Cyperus haspan*) plants arranged 15 cm apart (Astuty, 2006). Before sampling and analysis, the plants were adapted to the media for two days. The explanation can be clearly seen in the Figure 1.

Sampling and analysis

Testing began in December 2022. During this period, sampling and measurement of the pollutant parameter values were performed. The location of the sampling points is as shown in Figure 2. 60 liters of Tukad Badung River water was taken and sent directly to the greenhouse. Then 2 liters of water are taken first to be tested in the laboratory to determine the initial condition of the river water and the rest is poured into the reactor using a batch system. Processed water by the reactor was taken every 24 hours at the inlet and outlet of each wetland reactor, according to the scheme shown in Figure 3. And in Figure 4 is the lab-scale reactor wetland. As per SNI standards, the sample volume taken at each sampling point is 2L per day. This amount is used by calculating

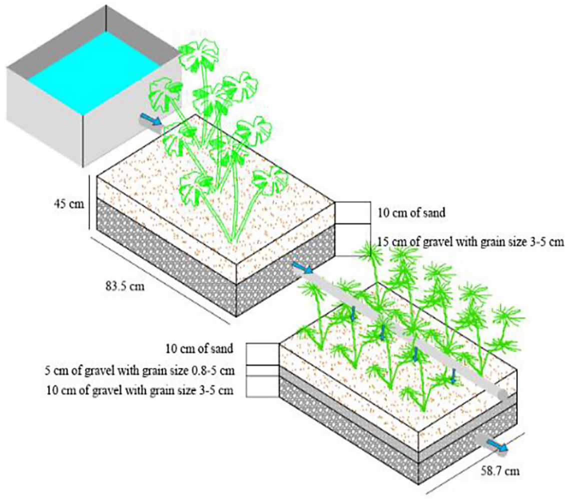

Figure 1. Lab-scale reactor wetlands scheme

the minimum sample volume required for each parameter, namely BOD, COD, TSS, and ammonia. The samples then immediately taken to the laboratory to measure pollutant parameter values.

Data analysis

The data were then analyzed to determine the efficiency of the wetland reactor during processing. The efficiency value or removal efficiency (RE) was calculated using Equation 2.

$$RE = 100\% \times (1 - Ce/Ci) \quad (2)$$

where: Ci and Ce are the concentrations of inflow and effluent pollutant parameters.

RESULTS AND DISCUSSION

The results of the analysis of the water samples taken from the influent and effluent of each constructed wetland reactor are presented in Table 1 and Table 2.

Tests on hybrid CW or CW terraces show relatively high removal efficiency values for several parameters, namely 93% for BOD, 82% for COD, and 96% for TSS. Meanwhile, ammonia showed a

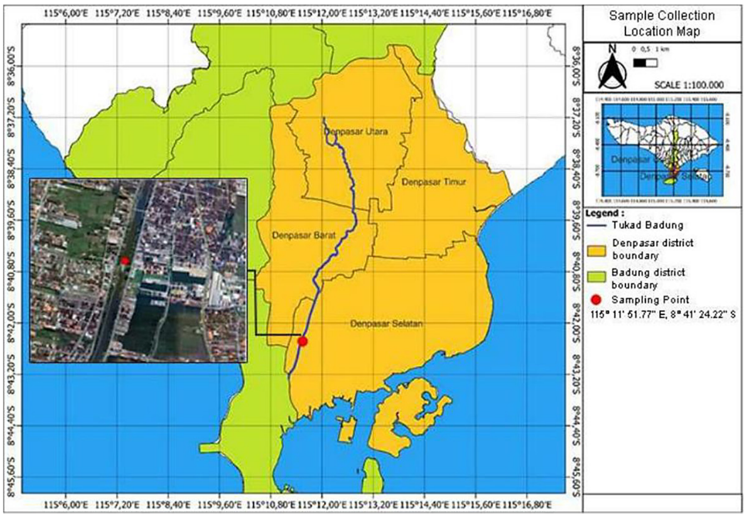

Figure 2. Sampling point in the Tukad Badung river

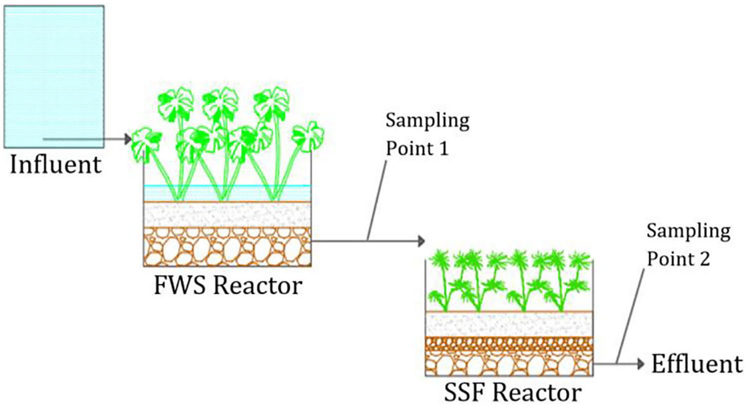

Figure 3. Sampling point scheme on each reactor

Figure 4. Lab-scale reactor wetlands

reasonably low removal value of 39%. Reviewed form previous research, this CW terracing system works about the same as other CW hybrids with a similar system, specifically HSSF-VSSF, as it has efficiencies of 86.4% for BOD, 76.72% for COD, 86.79% for TSS, and 44.9% for NH3 (Shi et al., 2004). However, in some studies, there is also higher efficiency, such as in the research of Abidi et al. (2009), with the efficiency of 83%, 87%, 81%, and 74% for the parameters BOD, COD, TSS, and TN (Abidi et al., 2009), and research by Singh et al., (2009) by combining anaerobic baffled reactor (ABR)-HSSF-VSSF with efficiencies of 90.1%, 90%, 95.9% and 69.5% for BOD, COD, TSS, and NH3 parameters (Singh et al., 2013).

CW is generally very effective in reducing organic matter from wastewater (Seres et al., 2017). The reduction in polluting organic matter, namely BOD and COD parameters, is strongly influenced by the activity of microbes that can decompose organic material, which can stick to leaves, stems, roots, and media or substrates (Saeed and Sun, 2012; Stefanakis et al., 2014; Wang et al., 2017). The results of the analysis of each parameter each day are shown in Figures 3–6.

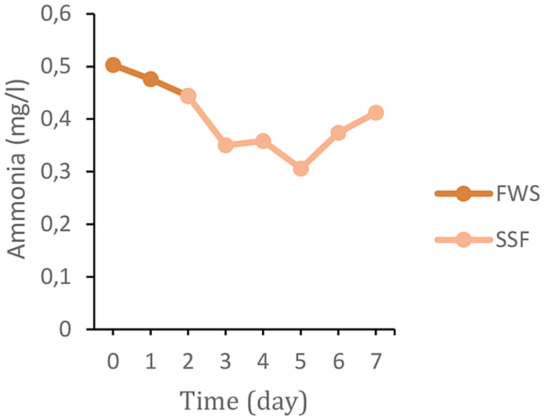

Figure 5. Result for ammonia parameter

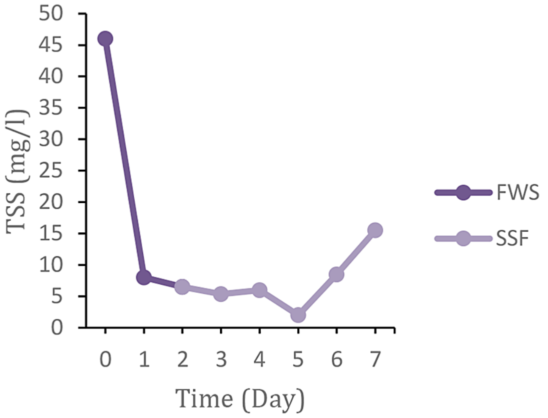

Figure 6. Result for TSS parameter

Table 1. Result of the analysis of water samples taken from the reactor day to day

Parameter	Influent	FWS Outlets (SP 1)		SSF Outlets (SP 2)				
		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7
BOD (mg/l)	8.06	4.03	4.03	<0.60	<0.60	<0.60	1.61	5.23
COD (mg/l)	20.4688	18.608	7.4432	5.5824	6.5128	3.7216	11.1648	13.0256
TSS (mg/l)	46	8	6.5	5.35	6	2	8.5	15.5
Ammonia (mg/l)	0.503	0.476	0.444	0.35	0.358	0.306	0.374	0.412

Table 2. Result of the analysis of removal efficiencies based on optimal reduction performance

Parameter	Influent	Sampling point 1 (SP 1)	Sampling point 2 (SP 2)	Total %RE
BOD (mg/l)	8.06	4.03	< 0.60	93%
COD (mg/l)	20.4688	7.4432	3.7216	82%
TSS (mg/l)	46	6.5	2	96%
Ammonia (mg/l)	0.503	0.444	0.306	39%

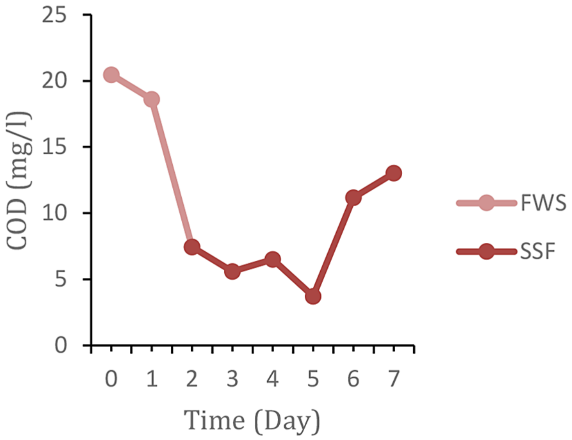

Figure 7. Result for COD parameter

The BOD in the FWS and SSF reactors was significantly reduced. In the FWS reactor, on the first day, the BOD parameter experienced a reduction of 50%, but this value remained stagnant. Therefore, there was no reduction on the second day. Meanwhile, on the first day in the SSF reactor, there was a reduction of approximately 85% in the BOD parameters. This value remained stagnant until the third day. However, on the fourth and fifth days, there was an increase in BOD parameters. On the fourth day, there was a negative value of -178%, while on the fifth day, there was a negative reduction of -213%.

In this system, organic pollutants are degraded both aerobically and anaerobically by microorganisms (Vasudevan et al., 2011). In addition to biochemical reactions, BOD reduction can also occur through physical processes such as the deposition and attachment of particulates to the substrate (Abou-Elela et al., 2017). Particulates that adhere to the substrate make it easier for microorganisms that grow on the surface of the media and plant roots to break down pollutants. Pollutants can be reduced through cooperation between plants and microorganisms (Shelef et al., 2013). However, the negative removal efficiency observed in this study could have been caused by the decay of plant organs in the substrate (Seres et al., 2017) and the formation of anaerobic conditions in the substrate. The higher the amount of organic material, the more oxygen the microorganisms requirehida (Hidayah et al., 2018). Therefore, if anaerobic conditions occur, the activity of organisms that decompose organic materials is reduced.

Plants play an essential role in oxygen provision. Oxygen from photosynthesis flows down the stem to the plant's roots, forming an oxygen-rich rhizosphere zone on the root surface (Suprihatin, 2014). This indicated that the water jasmine and papyrus plants in the FWS and SSF reactors could not release sufficient oxygen for the fourth and fifth days, thereby increasing the BOD parameters.

The FWS reactor showed a stable reduction in the COD parameters. A reduction of 9% was observed on the first day, and a reduction of 60% was observed on the second day. The SSF reactor showed three reductions, with negative values on the second, fourth, and fifth days. A reduction with positive values is indicated on the first and third days, with the lowest COD parameter value on the third day, namely 3.7216 mg/l. COD reduction occurs through degradation carried out by heterotrophic microorganisms, both anaerobically and aerobically (Priya and Brighu, 2013), as well as through physical processes such as sedimentation, filtration (Merino-Solís et al., 2015; Sudarsan et al., 2017) and deposition (Tilak et al., 2017). However, in reducing the COD parameters, physical processes are more important than biological processes (Sudarsan et al., 2017). The decrease in the COD parameters, as seen in Figure 2, indicates that the physical and biological processes in the reactor were running quite well. The decay of plant organs that remained in the substrate may have contributed to an increase in the organic load on the sixth and seventh days, which caused the increase in COD parameters. Non-biodegradable materials contained in the sample can also cause an increase in COD parameters (Abou-Elela et al., 2017). The TSS reduction in the FWS reactor was significantly reduced on the first day (83%). TSS reduction on the second day was 19%. Meanwhile, the SSF reactor showed several negative reduction values on days 2, 4, and 5.

TSS reduction is greatly influenced by filtration and sedimentation processes carried out by the substrate (Batool and Saleh, 2020). The SSF CW used in this study significantly influenced TSS reduction because the SSF CW system had the best ability to reduce TSS (Liu et al., 2019). The TSS removal efficiency of the CW with the SSF system is generally greater than 85% because of the effective filtration process by the substrate (Ji et al., 2022), so it follows the TSS reduction value obtained in this study, namely 96%.

Vyamazal et al. (1998) state that suspended solids are mostly removed through physical processes, such as sedimentation and filtration. Filtration occurs because of the trapping of solid particles in the roots and stems of macrophyte plants or in the substrate in the SSF system (Vymazal, 1998, 2013l). In this study, water jasmine plants growing in the FWS reactor have a robust root system at the bottom of the water, fast growth, can absorb a large amount of water in a short time, and also have root nodules that can associate with rhizosphere bacteria (Loshinta et al., 2020). In the SSF reactor, papyrus plants can accumulate large amounts of nutrients and have high biomass (Mburu et al., 2014). Root systems can provide more significant space for microbial growth, reduce water velocity, and strengthen settling and filtration in the root tissue, increasing TSS reduction efficiency (Abdelhakeem et al., 2016).

This study used gravel and sand as substrates for CW terracing. Substrate selection is crucial, the substrate not only provides physical support for plant growth but also provides additional space for biofilm growth and nutrient adsorption and promotes sedimentation and filtration of pollutants (Priya & Brighu, 2013; Zhu et al., 2012). Selecting a substrate that combines gravel and sand is very effective for sedimentation and filtration, as seen from the TSS reduction results, which reached 96%.

The most significant reduction in nitrogen, in the form of ammonia (NH_3), was observed in the SSF reactor on the first day (21%). The SSF reactor also showed negative reduction values on the third, fourth, and fifth days. Total nitrogen reduction is crucial when implementing Constructed Wetlands (Vymazal, 2013). In this test, the ammonia removal rate is 39%. The low ammonia inflow in the sample, 0.503 mg/l, can affect the removal efficiency. The higher the inflow concentration, the higher the processing efficiency (Cooper et al., 1990; Ghermandi et al., 2007; Seres et al., 2017).

Nitrification and denitrification are the main processes involved in ammonia reduction. The configuration and availability of dissolved oxygen to support the nitrification process are essential for reducing ammonia in CW systems (Mojiri et al., 2017). Constructed wetland configurations include factors such as climatic conditions, plant species, and interactions between microbial and plant colonies, as well as constructed wetland operating parameters such as hydraulic and pollutant loads, retention time, and water pouring methods, which can influence the performance of CW in reducing total nitrogen (TN), including ammonia (Akratos and Tsihrintzis, 2007; Lee et al., 2009; Saeed and Sun, 2012; Stefanakis et al., 2014). The method of pouring water into the SSF reactor by dropping water was proven to be more effective in reducing ammonia than pouring water into the FWS reactor. From the results of the ammonia parameters in Table 2, there was a more significant decrease in the SSF reactor than in the FWS reactor. The method of pouring water is poured vertically using holes made in the pipe to increase water contact with air, thus indirectly increasing the oxygen content in the water, which can support the nitrification process. Water is also dropped vertically in the FWS reactor through a tap, but the SSF reactor pouring method has a more significant number of water holes. Hence, the aeration process becomes more effective.

Plants also play a role in nitrogen reduction. Because nitrate ions and ammonia ions are essential for plant assimilation (Borin and Salvato, 2012; Lee et al., 2009; Stefanakis and Tsihrintzis, 2012) although in smaller percentages. Matheson and Sukias (2010) showed that plant uptake contributed around 9% of the total nitrogen reduction in the system, while 71% by nitrification and denitrification processes (Teknis et al., 2017). The gravel cleaned in this study also contributed to ammonia reduction through adsorption and deposition onto the active ingredients, although only in the initial process and not in the long-term (Lee et al., 2009).

The ammonia (NH_3) removal value, below 50% in this test, can also be caused by the lack of plant adaptation time to the substrate. The main process in the ammonia reduction mechanism is nitrification, which converts ammonia into nitrite or nitrate aerobically, and denitrification, which reduces nitrate into N2 gas under anaerobic conditions (Pramanik et al., 2012). The oxygen needed for the nitrification process in CW hybrids (FWS and SSF) is obtained from the atmosphere as a result of diffusion in the top layer and also by plant roots, which creates aerobic microsites along the plant roots (Lee et al., 2009; Schultze-Nobre et al., 2017; A. Stefanakis et al., 2014). Plant roots release oxygen into the substrate and establish aerobic conditions that facilitate microbial activity (Tian et al., 2017). Minimal adaptation time can result in plant roots being unable to maintain oxygen supply for the nitrification process, so the reduction in ammonia parameters does not occur optimally.

CONCLUSIONS

A laboratory-scale constructed wetland with a terracing concept, namely a combination of FWS and VSSF CW, has proven to be an option for treating Tukad Badung River water. This CW terracing achieved removal efficiencies of 93%, 82%, and 96% for BOD, COD, and TSS, respectively. In addition, the ammonia removal efficiency was 39%. The use of water jasmine (*Echinodorus palaefolius*) and papyrus (*Cyperus Haspan*) in the hybrid reactor, along with gravel and sand as substrates, gave good results in terms of the efficiency levels of BOD, COD, and TSS parameters. However, further studies are needed to increase the removal efficiency of ammonia parameters, such as optimizing the plant adaptation time. This research early indicate advantages, limitations, and possible applications of CW in Tukad Badung, future research will concentrate on examining various wetland configurations and conduct more experiments to further understanding of CW operations.

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