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Comparison of continuous and pulse mode of operation of pilot biosand reactors treating winery effluent

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ABSTRACT

In 2020 there was approximately 260 million hectolitres of wine produced across the world. Many winemaking and cellar cleaning activities generate winery wastewater. In vine growing areas which are water stressed, this wastewater is often used for irrigation and if it is inadequately treated it can be detrimental to land and aquatic environments. It has been shown at pilot scale that horizontal flow biosand filters are suitable for treating winery effluent to comply with irrigation standards. In this two-year study, vertical flow biosand reactors with novel design features were operated in both continuous and pulse modes of operation. It was envisaged that (i) the loading rates (organic and hydraulic) could be increased by changing the flow from horizontal to vertical flow, and that (ii) higher organic biodegradation rates could be achieved consequent to the increased redox potential from draw-down of atmospheric oxygen during system drainage in pulse mode in comparison to continuous mode. It was found that system performance was higher in continuous mode, attaining a hydraulic loading rate of 113 $L.m^{-3}$ of sand a day^{-1}, organic loading rate of 279 $gCOD.m^{-3}$ of $sand.day^{-1}$ and COD removal efficiency of 70% compared to pulse mode with 90 $L.m^{-3}$ of sand a day^{-1}, 192 $gCOD.m^{-3}$ of $sand.day^{-1}$ and 70%, respectively. In comparison to other passive winery wastewater treatment systems (constructed/treatment wetlands), these biosand filters are able to treat winery wastewater at higher loading rates with smaller spatial footprints.

1. Introduction

In 2020 there were approximately 7.3 million hectares under vine across the world, producing 260 million hectolitres of wine. Of this, 105.8 million hectolitres, valued at 29.6 billion Euros were exported (OIV, 2021). The practice of wine making relies on the beneficial processes which turn sugars into ethanol, as well as the formation of organic compounds which enhance the aroma and flavour of the end-product. Winemaking generates different waste streams, including winery wastewater (WWW). Due to different seasonal cellar activities, the quantity and composition of WWW fluctuates, not only seasonally, but also from cellar to cellar. Conventional secondary wastewater (WW) treatment systems require a consistent influent in both quality and quantity. Inconsistency may result in poor treatment performance during periods of heavy hydraulic and/or organic loading. In the case of WWW, treatment systems may also be redundant during several months of a year due to low flows, requiring repeated start-ups. For these reasons, WWW may not be adequately remediated if treatment systems are unable to adapt to rapid changes.

In water stressed areas such as South Africa, Australia and parts of the United States, WWW is often reused for irrigation of pastures or crops. Inadequately treated WWW can pose a threat to the soil and/or groundwater safety and security (Hirzel et al., 2017; Mosse et al., 2012).

Biosand reactors (BSRs), alternatively designated as biological sand filters, are similar to unplanted sand filled constructed/treatment wetlands (CW/TW). They are low cost, low maintenance, sustainable and energy efficient systems that can be used for treating WWW (Holtman et al., 2018; Mader et al., 2021). Biosand reactors have shown promising results for remediation of WWW, from laboratory-based experiments (Ramond et al., 2013; Welz and le Roes-Hill, 2014) to a pilot-scale reactor system (Holtman et al., 2018). They have proven capable of achieving high levels of treatment and providing safe effluent for irrigation while being able to readily adapt to the temporal changes of WWW and protracted shut down periods. A gravity-fed horizontal pilot system was able to effectively reduce the organic load and neutralise acidic WWW while increasing the sodium adsorption ratio (Holtman et al., 2018). The system was, however,r only suited to very small wineries because the achievable flow rates were low (402 $L.day^{-1}$). The

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low flow rates translate into large spatial footprints for the system.

In order to increase the flow rates in comparison to the original pilot BSR system while maintaining high organic removal rates (ORR), in-depth studies were conducted on more sophisticated, vertical flow BSRs with a novel design in-situ at a local winery in South Africa. These were operated alternately in either continuous or pulse mode over two crush seasons to ascertain which mode of operation yielded the most efficient performance. The operational and performance results are presented in the manuscript and results are compared with other passive systems treating WWW in terms of the hydraulic loading rate (HLR), organic loading rate (OLR) and ORR.

2. Materials and methods

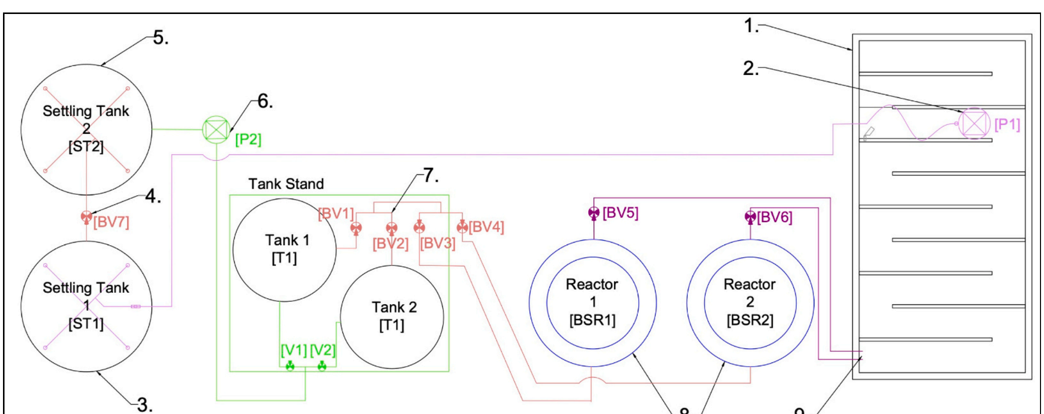
2.1. Set-up and operation of pilot scale biosand reactor system

The vertical flow BSR treatment system was a pilot system treating a fraction of the WWW. At full-scale, it is intended to treat a significant portion of the WWW generated by the winery in order to improve the overall quality of the effluent for irrigation, thereby protecting the soil environment. The treatment system was designed around the extraction of WWW from an existing baffled concrete solid settling delta to a series of holding tanks which acted as additional settling tanks and rudimentary anaerobic digestors (Fig. 1). Each BSR was inoculated evenly at the top with 500 g of sand from an existing horizontal flow BSR used to treat winery effluent. The sand was then further acclimated by intermittent feeding with WWW 3 months before the start of the crush season in year 1 of the study. Due to technical problems with the control system during start-up, the BSRs were not feed as often as planned.

The BSRs were fed with the settled, pre-digested WWW and the final effluent flowed via gravity back into the settling delta from where the effluent was fed into a holding dam used for irrigation (Fig. 1). More specifically, the WWW was extracted from the delta via a submersible sludge pump into a 5000 L settling tank (ST1) via 4 upward facing inlets when the liquid level in ST1 dropped to 50%. To reduce disturbance of solids, the inlets were located 1 m meter from the bottom of the tank. After a settling period of 120 min, the settled WWW was fed by gravity via a floating outlet pipe controlled by a 1″ full bore electronic ball valve into a second 5000 L settling tank (ST2). The outlet was located 10 cm below the liquid surface level of ST2 to prevent extraction of floating biomass or foam. After a settling period of 120 min, the WWW was extracted via a centrifugal pump to two 2500 L holding tanks (T1, T2) elevated on a steel tank stand. T1 and T2 were fed and emptied alternatively, the flows to T1 and T2 being controlled by two solenoid valves (V1 and V2). The two BSRs (BSR1, BSR2) were fed from T1 outlet controlled via BV1 or T2 outlet controlled via BV2 which were connected via a manifold. BSR1 inlet was controlled via BV3 and BSR2 controlled via BV4 while BSR1 outlet was controlled by BV5 and BSR2 by BV6. The system was set up so that BSR1 and BSR2 could be operated in continuous/pulse or continuous mode of operation. The entire systems' logic was controlled via a RievTech micro PLC (PR-14 DC-DA-R) and two expansion units (PR-E-16 DC-DA-R) and a series of analogue and digital inputs and relay outputs together with basic remote control via an Accentronix Infinity Cellswitch.

2.2. Sampling and characterisation of influent and effluent

Grab samples were extracted from sampling ports in ST1. Influent and effluent samples were taken from the influent lines to and outlet points to/from BSR1 and BSR2, respectively using the schedule provided in Table 1. Intense sampling (Table 1) and monitoring was conducted during the crush season only (Day 1 to 72 year 1 and day 1 to 58 year 2) because (i) approximately 61% of winery effluent is generated during the crush season at this winery (ii) the organic load is highest during the crush season (Welz et al., 2016), and (iii) it has already been shown that performance of BSRs is only under stress during the crush season (Holtman et al., 2018). Start-up commenced on 13th February in year 1 and sampling began on the 20th of February (day 1). BSR1 was operated in pulse mode and BSR2 in continuous mode from day 1 to day 43, after which the order was reversed until day 72. Similarly, in year 2 BSR1 was



1. Existing concrete settling delta
2. Submersible sludge pump [P1] extracts wastewater from the existing delta to [ST1].
3. [ST1] fills via 4 upward facing inlets 1 m above the bottom. Solids settling time = 120 min.
4. A 1″ ball valve [BV7] controls the gravity flow from 5000 L [ST1] to identical [ST2].
5. [ST2] is filled after the rest period of [ST1]. Both [ST1] & [ST2] have floating outlet pipes 100 mm below the surface.
6. Centrifugal pump [P2] extracts the settled supernatant from [ST2] and fills two 2500 L tanks [T1] & [T2] on tank stand. The flow direction is controlled by two solenoid valves [V1] & [V2].
7. Water flows alternatively via gravity from [T1] and [T2]. Flow and mode of operation is controlled by ball valves [BV1] and [BV2].
8. The Biosand reactors [BSR1 and [BSR2] can be operated in continuous or pulse fed mode of operation.
9. Treated wastewater is fed back into the settling delta

Fig. 1. Design layout schematic of the treatment system.

Table 1
Sampling schedule for the study period.

Influent and effluent to BSR1 and BSR2: COD, VOA, Total phenolics, pH, Electrical conductivity, TP, TN, Alkalinity, Na, Ca, Mg, K, P, Al	Influent and effluent to BSR1 and BSR2: COD, VOA, Total phenolics, pH, Electrical conductivity, Alkalinity	Settling tank: COD, VOA, Total phenolics, pH, Electrical conductivity, TP, TN, Alkalinity, Na, Ca, Mg, K, P, Al
Year 1 crush BSR1 pulse BSR2 in continuous mode		
Days; 1,10,14,16,22,29,34,37,43	Days: 6,24,27,31,38,41,45	Days: 16,37,43
Year 1 crush BSR1 continuous BSR2 in pulse mode		
Days: 50,57,64,72	Days: 48,55,59	Days: 50,57,64,72
Year 2 crush BSR1 pulse BSR2 in continuous mode		
Days: 1,8,22,36	Days: 3,6,8,13,17,20,24,27,31,34	Days: 1,8,22,36
Year 2 crush BSR1 continuous BSR2 in pulse mode		
Days: 43,52,57	Days: 38,41,45,55,58	Days: 43,57

BSR = biosand reactor, COD = chemical oxygen demand, VOA = volatile organic acid, TP = total phosphorous, TN = total nitrogen, ALK = total alkalinity, SALTS = Calcium, magnesium, potassium, sodium, aluminium and phosphorous.

operated pulse mode and BSR2 in continuous mode from day 1 to day 36, after which the order was reversed. Sampling and monitoring were terminated early in year 2 (day 58) because winery operations were interrupted due to an enforced hard lockdown as a result of the COVID-19 pandemic. Nevertheless, sufficient results were obtained in order to assess system performance. The system continues to operate effectively to date (year 4).

2.2.1. *Analytical procedures*

The concentrations of COD, total phosphorus (TP), total nitrogen (TN), alkalinity and volatile organic acids (VOA), were determined using a Merck (Merck®, Whitehouse Station, USA) Spectroquant® Pharo instrument and Merck Spectroquant® cell tests or kits according to manufacturer's instructions as previously described (Holtman et al., 2018). The total phenolic concentrations were determined using the Folin Ciocalteau method as previously described (Holtman et al., 2018).

2.2.2. *Determination of pH, temperature and electrical conductivity*

Probes were placed inside ST1 and ST2 to monitor electrical conductivity (EC, B&C C7335, K = 1.0, Carnate), temperature (PT100), pH (van London co. P822, Houston) and connected to an analog converter (Acdc Dynamics TRT-PT100). Data was recorded to an SD card connected to a micro PLC (RievTech PR-14 DC-DA-R and PR-E-16 DC-DA-R, Nanjing).

The pH of the lab samples was determined according to the manufacturer's instructions using a CyberScan pH 300 meter and appropriately calibrated pH probe PHWP300/02 K (Eutech instruments, Singapore).

2.3. *Calculation of operational parameters*

2.3.1. *Flow rates, volume of wastewater treated and electricity consumption*

The flow rate data was logged via two Kamstrup Multical 21 (02146VO1N94) 20 mm ultrasonic flow meters. This data was recorded by a Kamstrup Omnipower single phase electricity meter which also monitored the system's electricity consumption.

2.3.2. *Hydraulic conductivity, hydraulic loading rate, organic loading rate*

To counter biases from flow variability, the flow rate (Section 2.3.1) was converted to a 3-day lagging average for calculation of the HLR and OLR.

In CWs, the HLR or surface loading rate (SLR) and OLR are typically only calculated using the surface area of a wetland. In this study, the HLR and OLR were also determined using the entire volume of the reactor as previously described (Holtman et al., 2018; Mader et al., 2021). The ORR was determined by multiplying the OLR by the removal efficiency in terms of the COD.

3. Results and discussion

3.1. *Performance of biosand reactors*

The BSRs were evaluated in terms of (i) organic removal efficiency (COD, VOA, total polyphenolics), discussed in Section 3.1.1, (ii) inorganics and pH changes (pH, EC, alkalinity), discussed in Section 3.1.2, and, the (iii) hydraulic performance, discussed in Section 3.1.3. This is followed by (iv) a critical evaluation of the OLR, HLR and ORR that were achieved in the BSRs when operated in continuous and pulse modes, and comparison of the results to other passive systems treating WWW, discussed in Section 3.1.4.

3.1.1. *Organic removal performance*

The COD of samples for year 1 and year 2 are shown in Fig. 2A. Since an ideal pre-crush start-up/acclimation period could not be achieved in year 1 (Section 2.1), the COD removal efficiency was low (<50% for the first 3 weeks of operation). However, performance increased significantly over time. It can be seen in Fig. 2A that the COD concentration in the final effluent decreased with length of operation of the system during year 1. Overall, there was an average 88% (54–97%) COD removal efficiency in year 1 and 73% (33–93%) in year 2. The lower efficiency in year 2 may be attributed to differences in WWW characteristics and sampling periods related to variances in year-on-year cellar activities. The original vertical flow on-site pilot BSR system (Holtman et al., 2018) operated with a notably lower influent COD than the system described in this study over the two years of operation, however, COD removal rates were similar (70% vs. 79%), indicating notably superior COD removal performance with the new system. In terms of VOAs, in some instances they were formed within the BSRs as metabolic products, as previously demonstrated with WWW at laboratory scale and within settling basins (Welz et al., 2016; Welz et al., 2014).

Polyphenolics in WWW need to be reduced before discharge of the effluent because they may be toxic to microbes and plants (Arienzo et al., 2009; Mosse et al., 2011). In this study, the average removal efficiency of total polyphenolics during the monitoring period was 75%. The results compared favourably with the 77% (influent 18.4 mgGAE.L^{-1}) achieved with original horizontal flow system (Holtman et al., 2018) but at higher flow rates (Section 3.1.3). These results confirmed the ability of BSRs to effectively reduce polyphenolics in WWW.

3.1.2. *Assessment of pH and inorganic changes*

The pH of the WWW depends on the on the seasonal activities taking place in the cellar (Welz et al., 2016), but it is typically acidic (Vlyssides et al., 2005; Bories and Sire, 2010). In this study, the pH in ST1 ranged from 4.5 to 5.1 and 4.8 to 8.4 in year 1 and year 2, respectively (Fig. 3A). Overall, the BSRs increased the pH of the acidic effluent to >6 throughout the sampling periods. Similar results were found previously in a system containing sand from the same quarry site (Holtman et al., 2018).

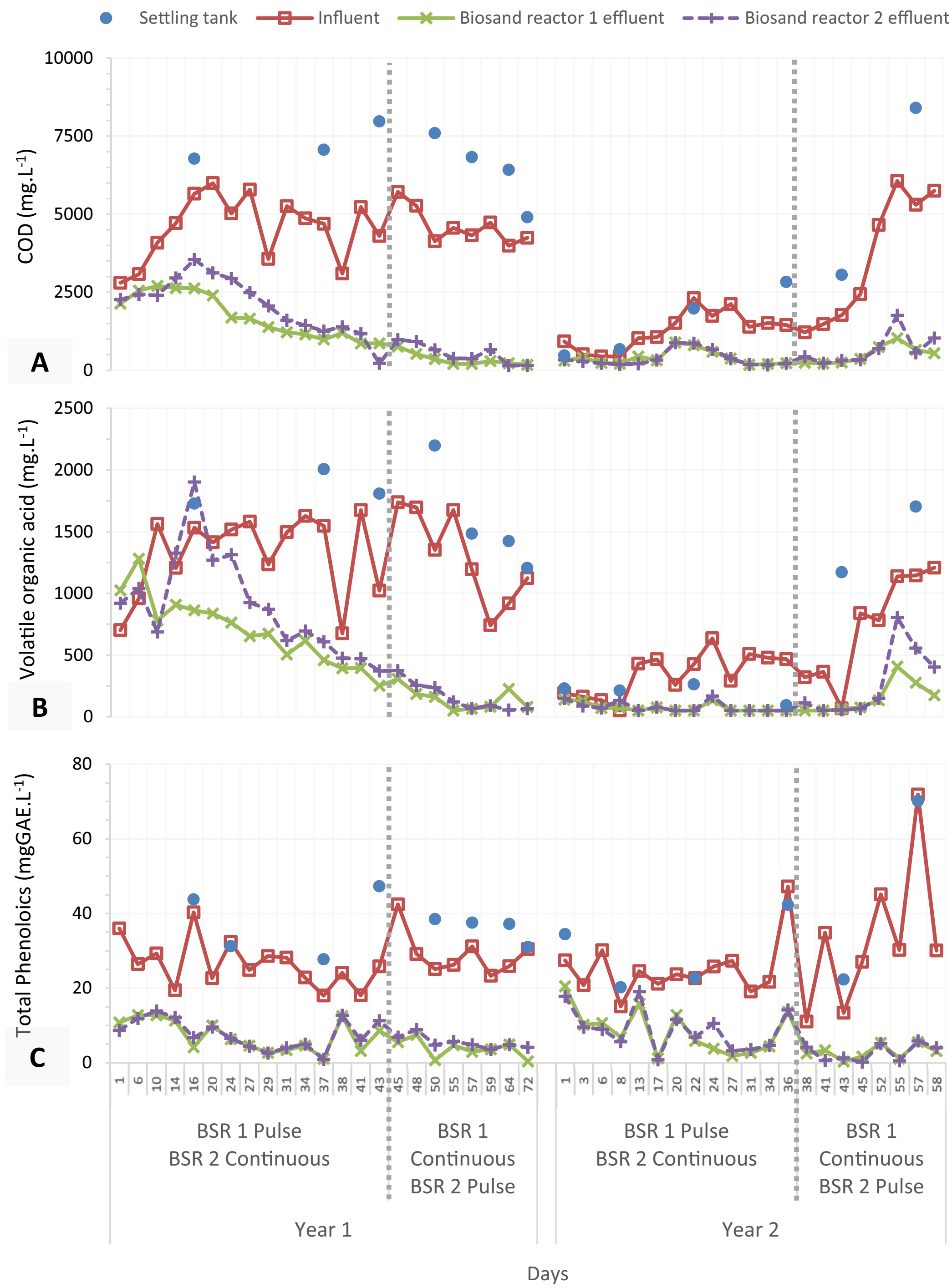


Fig. 2. The A) chemical oxygen demand, B) volatile organic acids, C) total phenolics samples taken from the biosand reactor treatment system during the pre-crush and crush period for year 1 and year 2.

The average electrical conductivity (EC) from ST1 for both periods was 1735 us.M^{-1} with respective averages for year 1 and 2 of 1690 us.M^{-1} and 1779 us.M^{-1} (Fig. 3C). Over the 2-year sampling period, the average EC increased by 75% from influent to effluent mainly due to the dissolution of calcite in the sand which was also responsible for pH buffering as previously described (Holtman et al., 2018; Welz et al., 2018a). The dissolution of calcite was also largely responsible for the increase in alkalinity from BSR inlet to outlet in year 1 and year 2 (Fig. 3C), also as previously described (Holtman et al., 2018).

The respective average influent TN and TP concentrations for year 1 were 1.4 mg.L^{-1} and 10.1 mg.L^{-1} and 31.8 mg.L^{-1} and 16.1 mg.L^{-1} in year 2 (data not shown). The average effluent concentrations from the BSRs in year 1 were 9.6 mg.L^{-1} TN and 2.4 mg.L^{-1} TP (ranges: 0 to 52 mg.L^{-1} and 0.2 to 24.4 mg.L^{-1} for TN and TP, respectively). In year 2, the average effluent TN from was 149.6 mg.L^{-1} (7.3–710 mg.L^{-1}) and average TP was 29.5 mg.L^{-1} (range: 4.8–67.5 mg.L^{-1}) (data not shown). The intermittent negative removal rates of TN may be attributed to microbial atmospheric N_2 fixation as previously described in BSRs (Welz et al., 2018b). From a practical perspective, the high effluent TP, and to a lesser extent high TN results may be seen as problematic in cases where

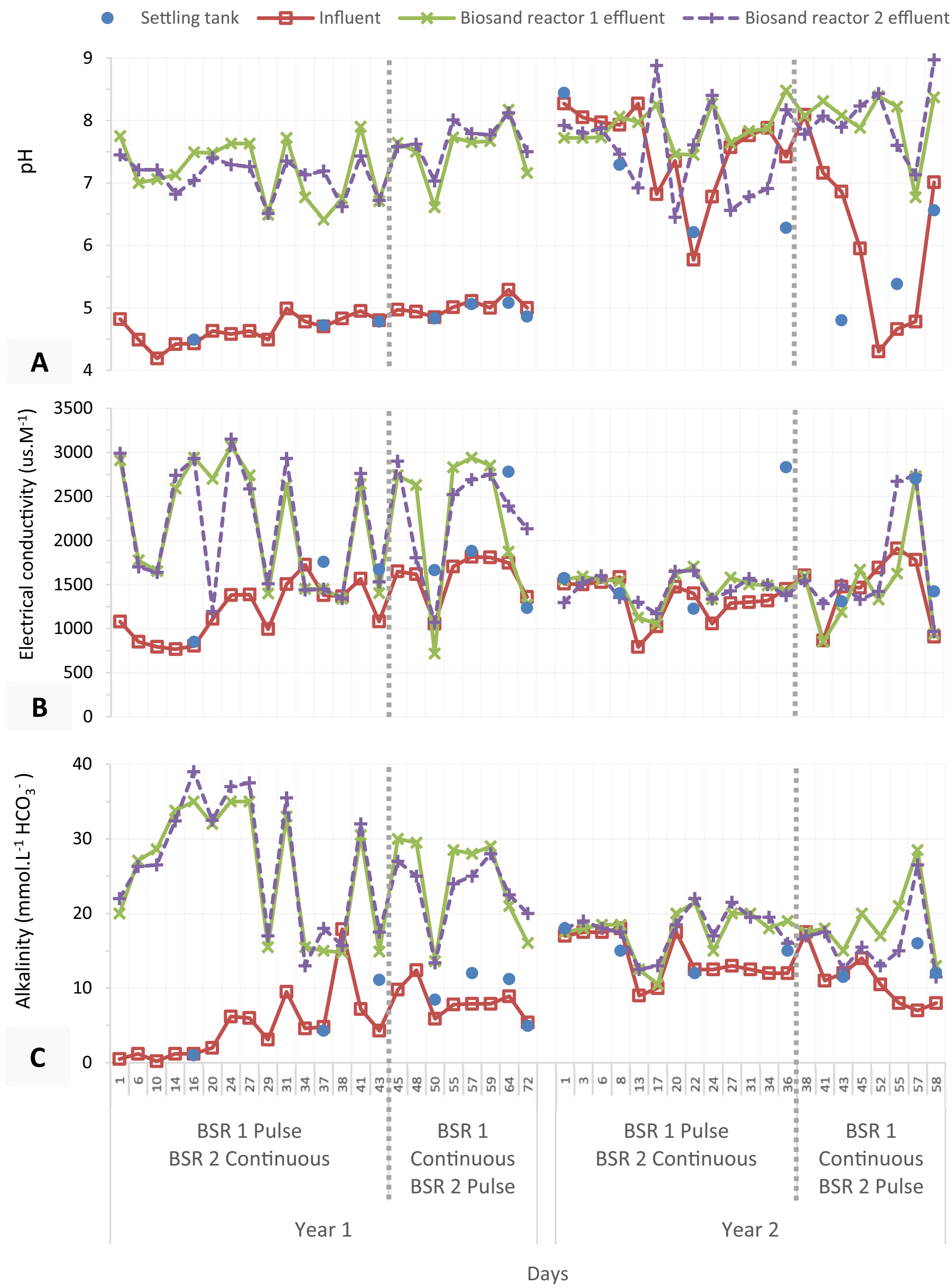


Fig. 3. The A) pH, B) electrical conductivity, C) alkalinity of samples taken from the biosand reactor treatment system during the pre-crush and crush period for year 1 and year 2.

the treated effluent is disposed directly to aquatic environments because of the risk of eutrophication. However, if the WWW is being used for irrigation purposes, as intended with the BSR systems, the presence of N and P is seen as beneficial as they are essential plant nutrients (Mader et al., 2021). Therefore, unlike many secondary wastewater treatment systems, removal of N and P is not a treatment objective.

3.1.3. Hydraulic capacity and performance

The BSRs used a novel design to increase the hydraulic performance while maintaining good pH neutralisation and organic removal performance, which was the primary objective of this study. It is envisaged that under normal operational circumstances, the fall across the BSRs (from the inside to the outside chamber) will be adjusted according to operational needs to increase or decrease flow rates, making the systems hydraulically versatile. In the study systems, the fall can be increased to up to 1700 mm during general operations to increase flow rates during high biomass and/or organic matter build-up (Fig. 4). However, for the purposes of the study, changes made to the fall during either of the two monitoring periods (year 1 and year 2 crush seasons) would have introduced an experimental variable, so no adjustments

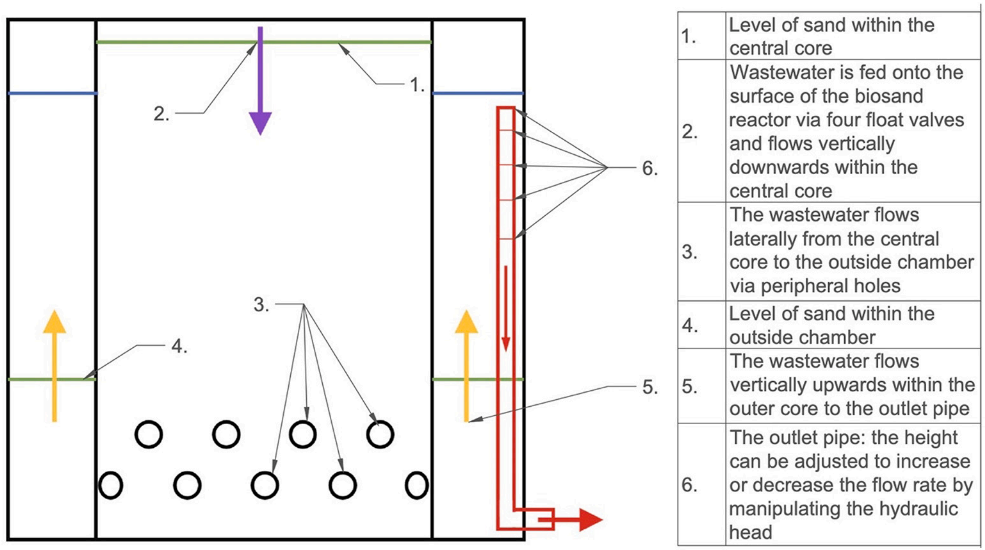


Fig. 4. Section view of the novel design of the biosand reactors.

were made during either year. Nevertheless, no permanent clogging occurred in the BSRs and the temporal reduction in hydraulic conductivity (HC) was attributed to accumulation of functional biomass (microbial growth). The novel design and unrestricted flow from the inner to outer core ensured no clogging within or at the outlets of the BSRs.

In year 1, the fall was maintained at 200 mm, with a sand height of 1500 mm. Over the year 1 crush period, the BSRs used on average 0.97 Kw.day^{-1} of electricity or 437 L.Kw^{-1}, to treat 30.2 m^3 of WWW at a flow rate of 425.3 L of WWW per day (205.5 L.day^{-1} and 219.7 L.day^{-1} in BSR1 and BSR2, respectively), with hydraulic flows of 659 L.day^{-1} and 483 L.day^{-1}, respectively over the first two weeks (results not shown). This reduced to a flow of $<$100 L.day^{-1} at the end of the crush season. It was theorised that the low flow rates were due to either (i) inorganic solids that may have entered the BSRs before the settling tanks were installed, and/or (ii) a lack in fall across the BSRs. Due to the unique design of the BSRs (Fig. 4), assumptions were made during the calculation of the fall that were not validated at a practical level. A new model was therefore applied that included a reduction in height of the sand in the outer chambers and reduction of the outlet height of the BSRs to increase the overall fall. It was calculated that this would result in an increase in treatment capacity to 1000 L.day^{-1} for each BSR.

The operation of the system was suspended at the end of the year 1 monitoring period. At this point, the flow of incoming WWW into the delta had reduced to an impractical rate, and the surface of the delta was covered with organic sludge that required removal. Some adjustments were made, and the fall was increased to 800 mm in year 2 with a sand height of 300 mm in the outside chamber. Over the year 2 crush period, the combined BSRs treated an average of 1017 L WWW.day^{-1}, and a total volume of 66.0 m^3 WWW and used on average 1.44 Kw.day^{-1} or 705 L.Kw^{-1}. The initial two-week flow rates were 790 L.day^{-1} and 1057 L.day^{-1} for BSR1 and BSR2, respectively. However, there was a reduction in flow rate over the treatment period to 500 L.day^{-1}. A build-up of organic matter was noted on the surface which was reducing the ingress of WWW into the top layer of sand, thereby reducing the overall HC of the BSRs. As with previous studies, the organic matter (including some microbial biomass) in the BSRs degraded during the off-crush period, restoring good flow rates (Holtman et al., 2018). This, however, takes time and does not rectify the problem experienced during the crush period itself. It is therefore suggested, as a simple remedy, that the organic layer is scarified in the affected areas on a weekly basis during the crush season to mitigate flow reduction in BSRs.

In the off-crush (non-monitoring) period of year 2, the system was restarted with both BSRs operated in continuous mode. Over the first week, the average flow rate was 3854 L.day^{-1} for both BSRs combined, showing the effect of increased fall on the initial rates and the potential recovery of HC due to biomass degradation. The rates then dropped to 871 L.day^{-1} and 426 L.day^{-1} for BSR1 and 2, respectively by the third week and reduced further thereafter. It was hypothesized that this was an artefact attributable to a partial blockage in the influent line entering the ultrasonic flow meters - for experimental purposes, the influent WWW flow rates were monitored by ultrasonic meters which have small pre-filters. The hypothesis was validated by the fact that electricity was still consumed by the pump and the PLC logged events during periods when the ultrasonic meter recorded no flow.

3.1.4. Hydraulic and organic loading rates

The treatment capacity of CWs, and by inference BSRs, is critical. Low HLRs translate into large spatial footprints with a larger area to source, operate and maintain. In CWs, the HLR/SLR and OLR are typically calculated using the surface area of the CW because they are limited by O_2 transfer to the root systems of the wetland plants. BSRs have no such limitations, and the loading rate calculations can be based on the cross-sectional area in the direction of flow, the functional surface area (FSA) (HLR_{FSA} and OLR_{FSA}) or the entire volume of the reactor (HLR_{Vol} and OLR_{VOL}). The latter are more accurate efficiency indicators, especially when comparing the efficiencies obtained with different types of media (Holtman et al., 2018; Welz et al., 2018a).

The performance of the BSR system was compared with previously published data on other passive systems (CW/TWs) treating WWW specifically focusing on systems with reported porosities, which ranged from 25 to 40% and in the different studies and this study 29% (Table 2). If provided, the OLR and HLR in these studies were reported as HLR_{FSA} and OLR_{FSA} in the cited manuscripts. Wherever possible, the HLR_{Vol} and OLR_{Vol} were also calculated from available data and included in Table 2. Loading rates in terms of the volume of reactors allow a more accurate comparison of the treatment performance of different media and operation modes (Holtman et al., 2018; Mader et al., 2021). However, this still includes the volume taken up by the inert media and actual biodegradation of the WWW takes place within the pore spaces. In order to more accurately compare the actual biodegradation rates (i.e. microbial activity) from system to system, this was calculated using the porosity of the media to calculate the volume of voids $V_{Voids} = V_{VLF} = V \times Porosity$ (Eq. 1) and this value to calculate the OLR in the void liquid fraction (OLR_{VLF}) $OLR_{VLP} = OLR_{Vol}/V_{VLF}$ (Eq. 2) (Table 2). The same equation (Eq. 2) was used to determine the HLR_{VLF} and ORR_{VLF} for comparison of the different systems.

Table 2
Comparison of operational and design parameters and performance of wetlands treating winery wastewater.

Area	Functional volume			Void liquid fraction			Reactor	Refs.
HLR	HLR_{Vol}	OLR_{Vol}	ORR_{Vol}	HLR_{VLF}	OLR_{VLF}	ORR_{VLF}	HTC	
$mm.d^{-1}$	$L.m^{-3}.d^{-1}$	$g\ COD.m^3.d^{-1}$	$g\ COD.m^3.d^{-1}$	$L.m^{-3}.d^{-1}$	$g\ COD.m^3.d^{-1}$	$g\ COD.m^3.d^{-1}$	$m^2.m^{-3}\ WW.d^{-1}$	
14.6*	41.7*	32.9 to 124.5	26.6 to 114.5*	131.7*	103.9 to 393.2*	84.2 to 361.7*	50.0	(Akratos et al., 2020)
7.3*	20.8*	16.4 to 62.1	13.3 to 57.1*	66.4*	52.3 to 198.2*	42.4 to 182.3*	100	
14	14 (VF)	152* (VF)	NG	UTC	UTC	UTC	9.6	(De La Varga et al., 2013a; De la Varga et al., 2013b)
24.8	43–82 (HF_1)	54* (HF_1)	38.3*	107.5–205* (HF_1)	135* (HF_1)	95.9* (HF_1)	57.7	
36.3	22–41 ($HF_{2,3}$)	27* ($HF_{2,3}$)	19.1	55–102.5* ($HF_{2,3}$)	67.5* ($HF_{2,3}$)	47.9* ($HF_{2,3}$)	57.7	
77–215	55–154* (VF)	31–333* (VF)	NG	UTC	UTC	UTC	9.6	(Serrano et al., 2011)
13–36	43–120* (HF_1)	12–183* (HF_1)	3.5 to 128.1*	107.5–300* (HF_1)	107.5 to 457.5* (HF_1)	29–320.3* (HF_1)	57.7	
13–36	22–60* ($HF_{2,3}$)	6.0–92* ($HF_{2,3}$)	1.4 to 64.4*	55–150* ($HF_{2,3}$)	50.0–230* (HF2,3)	3.5–161.0* ($HF_{2,3}$)	57.7	
34	28*	37–176*	35.9 to 174.2*	77.8*	102.8 to 488.9*	99.7 to 484*	29.8	(Shepherd et al., 2001a; Grismer et al., 2001; Shepherd et al., 2001b)
333*	150	152	120.1*	517.2*	524.1*	414*	17.8	(Holtman et al., 2018; Welz et al., 2018a)
23	1) 25*	1)350*	19.3 to 22*	65.7*	71.4 to 71.4*	55 to 62.8*	43.9	(Mulidzi and Africa, 2007; Mulidzi, 2010)
45	2) 50*	2) NG	UTC	142.9*	UTC	UTC	22.2	
78.3	57.0	260.4	177.0	196.6	897.9	610.3	13.3	This study Year 1
206.5	150.3	322.9	232.3	518.4	1113.4	801.1	5.6	This study Year 2

HF = horizontal (subsurface) flow COD = chemical oxygen demand VF = vertical (subsurface) flow, VLF = void liquid fraction. UTC = Unable to calculate, * = Calculated HLR_{Vol} = volumetric hydraulic loading rate, OLR_{Vol} = volumetric organic loading rate, ORR_{Vol} = volumetric organic removal rate HLR_{VLF} = void liquid fraction hydraulic loading rate, OLR_{VLF} = void liquid fraction organic loading rate, ORR_{VLF} = void liquid fraction organic removal rate, HTC = hydraulic treatment capacity, HLR = Surface loading rate.

In terms of the $HLR_{Vol,}$ results obtained during year 1 compared favourably with most other studies, while in year 2, the average HLR_{Vol} was higher than the other passive systems with the exception of other BSRs (Holtman et al., 2018; Welz et al., 2018a) and a gravel-filled horizontal flow CW (Serrano et al., 2011). The highest OLR_{Vol} applied was in a horizontal flow gravel-filled CWs at a large winery/distillery in South Africa (Mulidzi and Africa, 2007; Mulidzi, 2010). The primary reason for the high OLR_{Vol} was that the average influent COD was highest at this site (14,000 $mgCOD.L^{-1}$). Due to the average influent COD to the study BSRs being either higher (year 1: 4568 $mgCOD.L^{-1}$) or comparable (year 2: 2148 $mgCOD.L^{-1}$) to the remaining systems that were included in the comparison (535–4720 $mgCOD.L^{-1}$), and the relatively high HLR_{Vol}, comparatively high OLR_{Vol} were applied in the BSRs.

Most notably, in terms of the average $ORR_{Vol,}$ the BSRs substantially outperformed all of the other passive systems included in the comparison over the 2-year study period (Table 2). When the ORR considered only the void fraction of the different media (ORR_{VLF}), the difference in magnitude of the results obtained in the BSRs and the other systems increased even further (Table 2). These results strongly suggest that the sand used in the BSRs provides a superior matrix for attachment and activity of the functional microbes responsible for biodegradation of organics in WWW, a significant finding. The HLR, OLR and ORR of the BSRs during different modes of operation are provided in Table 3.

The BSRs were also compared with other passive treatment systems terms of the hydraulic treatment capacity (HTC) (Table 2), as systems that occupy large tracts of valuable land that can potentially be used for viticulture are not desirable (Bolzonella et al., 2019). The HTC was calculated as the area of land required to treat 1 m^2 of wastewater d^{-1} *HTC* = *Area/Flow* (Eq. 3). The spatial footprints of the BSRs were notably lower than all the other systems. Some of these systems consisted of more than one TW in series (Hirzel et al., 2017; Ramond et al., 2013; Welz and le Roes-Hill, 2014; Shepherd et al., 2001a), each having their own spatial footprint. The spatial footprint of the study BSRs of 13.3 $m^2.m^{-3}$ $WW.day^{-1}$ and 5.6 $m^2.m^{-3}$ $WW.day^{-1}$ for year 1 and 2 respectively was notably lower that for the other systems (22.2 to 150 $m^2.m^{-3}$ $WW.day^{-1}$).

Table 3
Comparison of parameters in different modes of operation: averages and (ranges).

Year	Filter	Mode	Period	Influent COD	RE	HLR_{Vol}	OLR_{Vol}	ORR_{Vol}
				$mg.L^{-1}$	%	$L.m^{-3}\ sand.day^{-1}$	$gCOD.m^{-3}\ sand.day^{-1}$	$gCOD.m^{-3}\ sand.day^{-1}$
1	BSF1	Pulse	First	4541 (2800–5990)	59% (17–84)	74 (24–44)	288 (82–1236)	133 (33–294)
	BSF2	Continuous			52% (19–95)	91 (0–526)	433 (0–3151)	180 (0–1510)
1	BSF1	Continuous	Second	4619 (3990–5710)	93% (87–96)	13 (3–22)	59 (15–124)	54 (14–108)
	BSF2	Pulse			89% (83–96)	7 (0.1–15)	32 (0.4–67)	28 (0.3–62)
2	BSF1	Pulse	First	1265 (441–2310)	63% (20–87)	177 (52–540)	190 (42–394)	114 (22–257)
	BSF2	Continuous			67% (42–89)	208 (3–717)	216 (4–985)	130 (4–310)
2	BSF1	Continuous	Second	3583 (1217–6060)	85% (80–90)	102 (29–207)	311 (101–638)	266 (87–536)
	BSF2	Pulse			81% (64–89)	61 (0.5–176)	176 (3–591)	149 (2–502)

BSR = biosand reactor, RE = removal efficiency, HLR_{Vol} = volumetric hydraulic loading rate, OLR_{Vol} = volumetric organic loading rate, ORR_{Vol} = volumetric organic removal rate.

3.2. Comparison of pulse and continuous mode of operation

The BSR systems were designed to allow different modes of operation. While continuous operation is simple, some researchers have shown that increased ORR may be achieved with intermittent or pulse operation modes. In order to definitively establish the preferential mode of operation, each BSR was operated alternatively in continuous and pulse mode each year during the crush periods (Table 1) and results were compared (Table 3).

3.2.1. Hydraulic and organic loading rates

On average continuous mode had greater HLR, OLR and ORR, outperforming pulse mode by average magnitudes of 21%, 31% and 30% respectively over the 2-year experimental period (Table 3). The ORR_{Vol} of VOA was 28% higher in continuous mode, and there was no difference in total phenolic removal efficiencies between the two modes (results not shown).

While the organic degradation of WWW relies on the microbial populations in BSRs and other similar systems, the HC decreases, and the HRT increases as a consequence of the functional microbial biomass which attaches to the inert medium and reduces the porosity. This retards the flow, but the increased HRT typically results in higher ORR (Welz et al., 2018a). There is a critical balance between HLR (and HRT) and system operation and performance. Systems operated with low HLR require large treatment plants with associated capital and operational costs and large spatial footprints, while the performance of those operated with high HLR (and low HRT) may be inefficient (Holtman et al., 2018; Juwarkar et al., 2010; Semple et al., 2007). In BSRs, higher HLR can be achieved by manipulating the hydraulics within the system by: (i) increasing the fall, (ii) adjusting the loading rates, and/or (iii) intermittent operation (Juwarkar et al., 2010; Semple et al., 2007; Achak et al., 2009; Knowles et al., 2011). Generally, the top layer of media or area around the inlet of TWs/CWs has the greatest accumulation of biomass. Several operational methods have been used to negate excessive biomass build-up, namely: (i) back washing, (ii) scarifying the surface layer, (iii) applying higher HLR to flush the solids out, and (iv) changing the direction of flow or areas of ingress to allow accumulation of biomass to dissipate during the rest period (Nivala et al., 2012). Then there are methods which involve the total or partial removal and replacement or offsite cleaning of the media which does have significant financial constraints (Nivala et al., 2012). Some of these methods involve the degradation of the biomass within the systems themselves. In this study, it was envisaged that the intermittent aerobic/anoxic conditions created by fill and drain cycles during pulse mode operation would result in reduced biomass and concomitant increased HC within the BSRs as described by Nivala et al. (2012). In addition, the drain cycle introduces air into the media which exposes the biomass to O_2. The O_2 is used as a terminal electron acceptor for aerobic heterotrophic metabolic processes, which are energetically more favourable than anoxic or anaerobic metabolic processes (Nivala et al., 2012; Maier et al., 2009; Torrens et al., 2009). However, when the BSRs were operated in pulse mode, the sand remained saturated after the drain cycle. A significant increase in drain cycle time was required to achieve a meaningful aerobic period. It was decided that this was not warranted as the hydraulic treatment capacity would be severely impacted. In addition, it has previously been shown that, contrary to expectations, higher degradation of ethanol and phenolics in synthetic WWW takes place in lower redox environments in sand-filled treatment systems, albeit with accumulation of VOAs which are formed as metabolic by-products (Welz and le Roes-Hill, 2014; Welz et al., 2016; Welz et al., 2014). The higher accumulation of VOAs in continuous mode of operation supports these previous findings.

Overall, it is recommended that due to the comparative operational simplicity, greater volumetric hydraulic loading, organic loading, and organic removal rates, that the systems are operated in continuous mode.

4. Conclusion

This study showed that continuous mode of operation of BSRs outperforms pulse mode of operation in terms of HLR, OLR, ORR by 21%, 31% and 30% respectively. The novel BSR systems provide a small spatial footprint compared to similar passive treatment systems with a reduction in the reactors special footprint ranging from a 40% to 96%. The systems provide a conducive environment for functional microbial growth and activity, allowing treatment of WWW at high ORL_{VLF} with no evidence of permanent clogging. These systems require minimal outside interference and do not require skilled labour for operation. Future designs should have outlets at different heights spaced 200 mm apart to allow more simple manipulation of flow rates.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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