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Biological sand filter system treating winery effluent for effective reduction in organic load and pH neutralisation

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ABSTRACT

Wineries generate 0.2–14 L of wastewater per litre of wine produced, which is often used for irrigation or discharged into aquatic systems. To mitigate adverse environmental impacts, there is a need for low cost wastewater treatment options. The novel biological sand filtration system described in this pilot study is a sustainable off-grid modular system which can be easily retrofitted to current infrastructure. The system was operated with average hydraulic and organic loading rates of 150 $L\,m^{-3}$ sand.day^{-1} and 152 gCOD.m^{-3} of sand.day^{-1}, respectively. Over 762 days of operation, average removal efficiencies of 79% and 77% in terms of chemical oxygen demand and total phenolic concentrations were achieved. In addition, an average 1.8-fold increase in the calcium concentration was achieved, with a concomitant reduction in the sodium adsorption ratio and similar indices. This pilot study also confirmed in a 'real world' setting the results of laboratory-based studies where biological sand filters neutralised acidic synthetic winery wastewater and reduced the organic load.

1. Introduction

Wine production can be water-intensive. In addition to vineyard irrigation requirements, an estimated 0.2–14 L of water is needed to produce 1 L of bottled wine [1–3]. Most of this water leaves the cellar in the form of winery wastewater (WWW) that is typically acidic, and contains organic and inorganic fractions associated with seasonal cleaning activities [3,4]. The character and volume of the WWW varies on a temporal basis, with a pattern of high organic to inorganic load during the crush season, and vice-versa during the non-crush period [5].

In many countries, including South Africa, Australia, and the United States, WWW is often re-used for irrigation of pastures or crops in water-stressed areas; unless adequately treated, WWW may pose a threat to the soil environment and/or groundwater [6–8].

Many treatment processes have been researched and/or applied for the treatment of WWW, including: physicochemical processes, biological processes, membrane filtration and separation processes, and advanced oxidation processes [9]. Membrane systems have not been widely adopted by the wine industry because of the high capital outlay and operating costs, the propensity for membrane fouling, and brine generation [10,11]. Physicochemical processes rely on either sedimentation, precipitation, coagulation/flocculation, or electrocoagulation [9]. Currently, the most effective physicochemical and advanced oxidation processes require skilled to semi-skilled labour, chemical inputs, create solid waste streams, and need to be used in conjunction with biological treatment methods to achieve satisfactory organic removal rates [10,11].

While biological systems such as rotating biological contactors, upflow anaerobic sludge blankets and membrane bioreactors may be suited to larger wineries for biodegradation of WWW organics, there is a global need for simple, low maintenance, cost effective systems at small wineries that do not have the finances or personnel to operate complex systems [9]. Many wineries utilise anaerobic or aerated ponds. These are simple and cheap to operate. However, odour problems are associated with ponds, and long hydraulic retention times (HRTs) are required, which translates into a large spatial footprint [12,13]. Constructed wetlands (CWs) are an effective option if the WWW is diluted or mixed with domestic wastewater (WW) [14,15].

The main drawback of CWs is that (poly)phenolic-rich effluent such

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Abbreviations: WWW, winery wastewater; WW, wastewater; HRT, hydraulic retention time; CW(s), constructed wetland; OMWW, olive mill wastewater; COD, chemical oxygen demand; BSF(s), biological sand filter; k, hydraulic conductivity; VOA(s), volatile organic acid; AAC, acetic acid equivalents; SAR, sodium adsorption ratio; CROSS, cation ratio of soil structural stability; Q, flow rate; T, time; V, volume; OLR, organic loading rate

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as olive mill wastewater (OMWW) and WWW is phytotoxic [14,16–19]. For example, Shepherd et al. [19] demonstrated that gravel-filled horizontal subsurface flow CWs were able to achieve 97% COD removal when treating WWW with chemical oxygen demand (COD) concentrations $< 5000\,\text{mg}\,\text{L}^{-1}$, but poor removal efficiency was achieved and plants died at COD concentrations of $12\,800–16800\,\text{mg}\,\text{L}^{-1}$. It can also be argued that the inclusion of plants in CWs treating WWW is unnecessary because they play a limited role in reducing COD and suspended solids, they require periodic harvesting, and their roots can facilitate the formation of preferential flow paths [16,20].

Biological sand filters (BSFs) can be seen as unplanted CWs. The sand creates a physical substrate for biofilm attachment, can adsorb pollutants, catalyse chemical transformations, and provide metabolic co-factors; the functional microorganisms within the biofilm are responsible for biotransformation, biodegradation and mineralization of chemical pollutants [24]. In a series of fundamental laboratory-based experiments, it was shown that simple BSFs containing ungraded locally-available dune sand [21] were able to cope with the temporal nature of WWW and achieve reliable removal of organics, including (poly)phenolics [22,23]. To determine whether BSFs are viable for the treatment of WWW is a 'real-world' setting, a pilot system was designed, installed and operated at a wine farm in the Stellenbosch area close to Cape Town, South Africa. This manuscript details and analyses the performance of the system over approximately 27 months.

2. Materials and methods

2.1. Set-up and operation of pilot scale biological sand filtration system

The BSF system consisted of a number of connected polyethylene (PE) containers: a 5000 L collection tank, a 500 L holding tank, 4 × 1000 L sand filter modules, and 4 × 100 L flow-control tanks. The system was connected to an existing 45 m^3 baffled concrete solids-settling delta (Fig. 1A). A fraction of the WWW from the delta was treated and returned to the head of the delta, thereby improving the quality of the WWW which was used to irrigate a sheep pasture.

The WWW from the cellar gravitated into the delta inlet and settled effluent was pumped from the delta outlet to the 5000 L collection tank using a Shurflo (Pentair, Minneapolis, USA) 2088-313-145 12 V DC diaphragm premium demand solar pump. The pump was controlled by a liquid level relay and a probe within the 5000 L collection tank, which was set to fill the collection tank to 3800 L when the volume dropped to 2500 L. The flow through the remainder of the system was controlled by gravity, float valves and adjustable flow-control tanks (Fig. 1B). The float valves and flow control tanks enabled the HLR to be automatically altered when the flow rates through the filters increased or decreased. A constant head of 30 cm was maintained across each filter module. The modules were filled with a locally available dune sand, which had previously been well characterised and found to be suitable for use in BSF in terms of treatment capacity and hydraulic conductivity (k) [21]. The system could be operated in parallel or series, and was operated in parallel during the experimental period.

2.2. Sampling and characterisation of influent and effluent

Influent was defined as the grab WW samples from the 5000 L collection tank, and the effluent as the final effluent (Fig. 1). During the final year of the study, the sampling regime was increased for more accurate assessment of BSF performance (Table 1). In addition to regular monthly or bi-weekly analyses, a once-off batch test was performed, which entailed hourly sampling (Table 1). In three scheduled sampling instances, no samples could be taken due to operational problems (Dec 2015, Jan 2016, Mar 2016).

2.2.1. Determination of chemical oxygen demand, nutrients, and selected organic fractions

The COD, total phosphate and total nitrogen concentrations were determined using a Merck (Merck®, Whitehouse Station, USA) Spectroquant® Pharo instrument and Merck Spectroquant® COD cell tests for low, medium and high range samples (cat. no. 1.14895.0001, 1.14541.0001 and 1.14691.0001) and total nitrogen cell tests 1.14543.0001 and total phosphate as PO_4-P 1.14537.0001 according to manufacturer's instructions., according to the manufacturer's instructions. The total phenolic concentrations were determined using the Folin-Ciocalteu micro method based on that described by Slinkard and Singleton [25] using Merck®Folin–Ciocalteu reagent (Cat No: 1.09001.0500). The concentrations of volatile organic acids (VOAs) were determined using the Hach (Loveland, USA) esterification method (cat no 8196) in accordance with manufacturer's instructions with some modifications: 3 standard concentrations of acetic acid were prepared ($945.00\,\text{mg}\,\text{L}^{-1}$, $472.50\,\text{mg}\,\text{L}^{-1}$ and $236.25\,\text{mg}\,\text{L}^{-1}$) and were used to prepare a standard graph for the determination of the VOA concentrations in acetic acid equivalents (mgAAC.L^{-1}).

2.2.2. Determination of pH

The pH of the samples was determined according to the manufacturer's instructions using a CyberScan pH300 meter and appropriately calibrated pH probe PHWP300/02 K (Eutech instruments, Singapore).

2.2.3. Sodium adsorption ratio, cation ratio of soil structural stability

Concentrations of sodium, potassium, calcium and magnesium were determined using a Varian® MPX inductively coupled plasma optical emission spectrophotometer (Agilent Technologies, Santa Clara, USA) at Bemlab (Pty) Ltd. (Strand, South Africa). The sodium adsorption ratio (SAR) and cation ratio of soil structural stability (CROSS) were determined using the equations described by Marchuk and Rengasamy [26] and Oster et al. [8].

2.3. Calculation of operational parameters

2.3.1. Flow rates and volume of wastewater treated

The flow rate was determined by measuring the volume of water collected from the outlet over the period of one minute. Measurements were taken in triplicate, averaged, and converted into the daily flow rate (Q).

Q was used to determine the volume of WWW treated and was estimated using 2 methods: (i) the average of all the measured flow rates (Table 1) and (ii) a trapezoidal equation Eq. (1) that assumed a linear decrease or increase in Q between measuring instances (t).

$$\sum Vol_n = Q_{n-1}(t_{n-1}) + 0.5[(Q_n - Q_{n-1})(t_{n-1} - t_n)] \tag{1}$$

2.3.2. Hydraulic retention time, hydraulic conductivity, hydraulic loading rate, organic loading rate

The saturated cross-sectional area at the discharge point was used in combination with the change in height (h) divided by the change in length (l) to determine k in terms of Darcy's law Eq. (2) [27,28]. The HRT was determined using the volume (V) of liquid within a packed media divided by the flow rate as shown in Eq. (3) [29], while the volume of liquid was determined by multiplying the porosity of the substrate by the volume of the reactor.

The HLR was expressed in two different ways: (i) as the discharge rate of influent divided by the volume of the reactor ($\text{L}\,\text{m}^{-3}\,\text{d}^{-1}$) Eq. (4), and (ii) as the discharge rate divided by the cross-sectional area of the reactor ($\text{L}\,\text{m}^{-2}\,\text{d}^{-1}$), which is the formula typically applied for reactors operated in horizontal mode Eq. (5). The organic loading rate (OLR) was determined by multiplying the influent flow rate by the influent COD or BOD concentration divided by the volume of reactor [29] Eq (6).