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Biosand reactors for remediation of winery effluent in support of a circular economy and the positive effect of sand fractionation on hydraulic and operational performance

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A R T I C L E I N F O

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A B S T R A C T

There is an extensive body of knowledge pertaining to the treatment of winery wastewater and other acidic effluents in biosand reactors. This manuscript compares the performance of biosand reactors containing raw sand and fractionated sand. Fractionation of sand (particles <0.425 mm removed) increased the hydraulic conductivity of the sand matrix 9-fold when compared to raw sand: from 0.285 mm·s^{-1} to 2.50 mm·s^{-1} and 0.129 mm·s^{-1} to 1.11 mm mm·s^{-1} before and after start-up, respectively. Similar results for both sands were obtained in terms of organic removal performance (94 % and 95 %, respectively) and neutralization of acidic (pH 4.9) winery wastewater. Results indicate that one 5.6 m^3 biosand reactor module containing 2.9 m^3 of fractionated sand can theoretically treat 8102 L·d^{-1}, which is the approximate volume generated from wineries crushing 329 to 547 t of grapes per annum. This is notably higher than the design flow rate of 1000 L·d^{-1} in used in a pilot system containing raw sand. Furthermore, a zero-waste biosand reactor model is presented for treatment of winery wastewater. The strategy includes reuse of treated effluent for irrigation, anaerobic digestion of primary winery wastewater sludge and use of the digestate as an agricultural fertilizer, and re-purposing of the residual sand.

1. Introduction

Fermentation of grape juice to wine relies on the microbially mediated conversion of grape sugars to ethanol with the concurrent formation of other metabolites which add to the complexity of the final product [1–4]. This winemaking process and ancillary operations generate solid wastes, by-products, and winery wastewater (WW). Many solid waste streams, including lees and marc, are valorised on-site or in dedicated biorefineries [5], but due to its nature, WW has little beneficial use. Winery wastewater fluctuates in physiochemical quality, with the highest organic and volumetric loads occurring during the crush/harvest period [6–8]. After primary settling and pH adjustment, 'beneficial' irrigation is often used as a means of WW disposal, particularly in water stressed countries [9]. Depending on cellar activities and practices, the WW can contain high concentrations of organic molecules and inorganics. For example, high sodium (Na) loads can emanate from the ubiquitous use of the relatively inexpensive and effective cleaning product, sodium carbonate (Na_2CO_3) [6]. Polyphenolics in WW can be phytotoxic, and highly saline WW may cause some soils to become sodic [6,10–12]. Irrigation with untreated WW can therefore pose a threat to the receiving environment. It is therefore prudent to remediate WW before discharge on land or to aquatic environments.

There are several WW treatment options available which vary in cost, complexity, and efficiency. The challenge for designers of WW treatment systems is the seasonal variability in the quality and quantity of WW [13–15]. Depending on the local legislation, the amount of WW generated, and the location of the cellar, different levels of remediation may be required. While complex treatment systems may be effective, they are generally not applicable for smaller wineries due to cost and staff constraints [16]. Constructed/treatment wetlands have been extensively used as passive WW treatment systems, but typically have large spatial footprints and the WW may be phytotoxic to the plants [17]. Biosand reactors (BSRs), alternatively known as biological sand filters or unplanted constructed/treatment wetlands, are cost effective, require minimal maintenance and provide an environment for biodegradation of the organic fraction of WW and neutralization of acidic WW.

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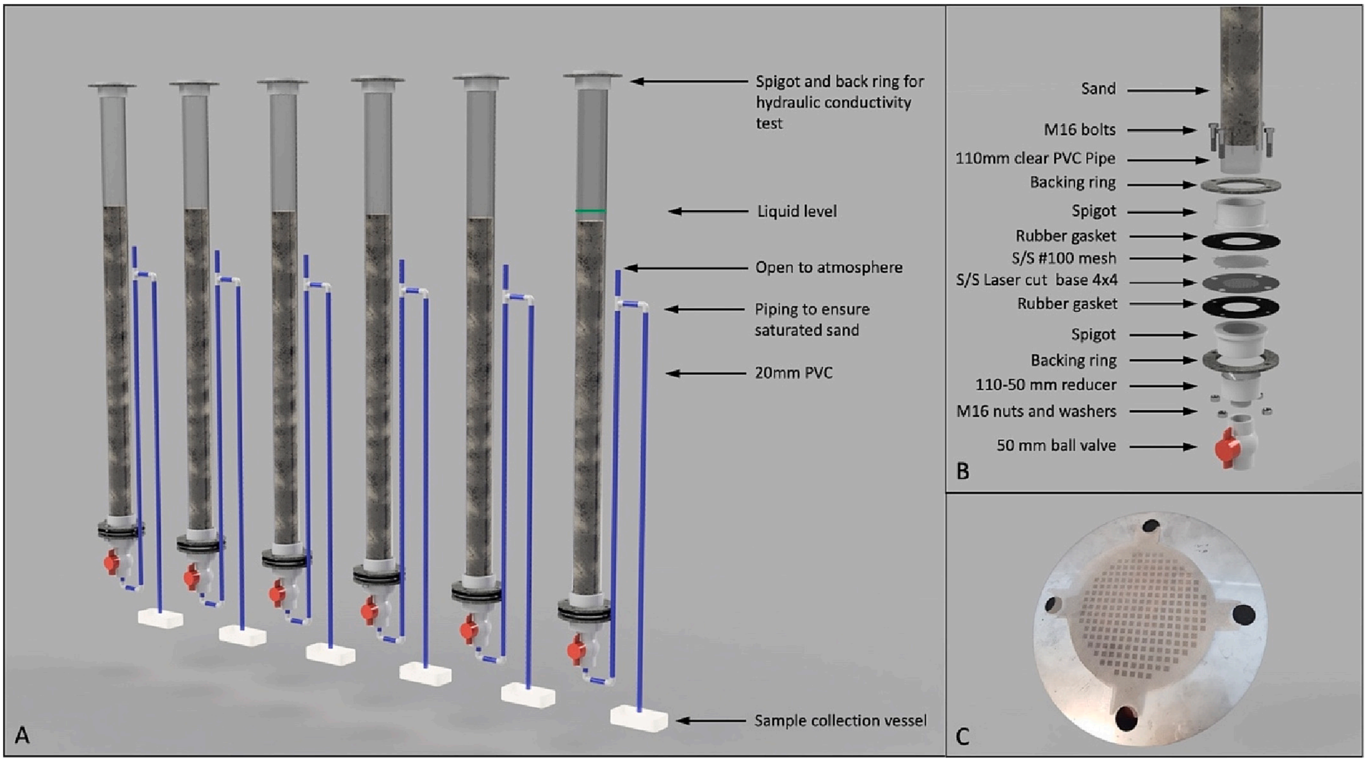

Fig. 1. Layout of experimental set-up of column experiment together with outlet piping (A), exploded view of outlet filter of column (B), stainless steel number 100 mesh and the stainless-steel laser cut base with 4 × 4 mm square openings (C).

After start-up, the hydraulic conductivity (HC) of the BSRs decreases due to the formation of functional biomass. This is inversely correlated with organic loading and therefore reversible, so that the systems do not require backwashing after the crush season even after long-term operation [18–21]. When operated in vertical mode, BSRs have smaller spatial footprints and higher specific organic removal rates (ORR) than other passive treatment systems, and can be retrofitted to existing treatment systems [21].

One of the challenges that has previously been associated with pilot BSRs is the large (up to 95 %) reduction in the HC of the sand due to build-up of biomass during WW treatment [21]. The biomass is a necessary functional component of BSRs and is most abundant during periods of high organic loading. During this time, it retards the flow of WW, causing a transient reduction in the hydraulic capacity of BSRs [18,21,22]. The size of sand particles is a critical factor governing the HC of soil and sand environments, with liquid flow rates increasing as particles increase in size [22,23]. It was therefore hypothesized that: (i) the hydraulic performance of BSRs during the crush period could be improved by fractionating the sand and using only the larger sand particles in the systems, and (ii) the smaller sand particles could be used for another purpose. For example, smaller sand particles are more desirable in self-compacting concrete (SCC) mixes [24]. The proposed dual usage of the sand feeds into the principles of a circular economy.

In passive treatment systems, there is theoretically a balance between hydraulic retention time (HRT) and remediation efficiency [25,26] and functional microbial communities are influenced by the character of sand particles in BSRs [27]. It was therefore recognized that the fractionation strategy could have a negative impact on BSR performance. Column replicates containing raw or fractionated sand (particles >0.425 mm) were therefore used to compare (i) The HC before and after build-up of biomass consequent to feeding with WW, (ii) organic removal rates, and (iii) WW neutralization rates. This study is the final in a series of studies pertaining to remediation of WW in BSRs. The manuscript therefore contains a section exploring the holistic use of BSRs and proposed ancillary methods for treating WW and WW sludge in the context of resource utilization and reuse for a bio-circular economy.

2. Materials and methods

2.1. Experimental set-up and operation

The experimental set-up consisted of six identical clear 2000 mm tall polyvinyl chloride (PVC) columns with internal diameters of 105 mm (Fig. 1A). Each column contained approximately 20 kg of sand to a height of 1450 mm (Table 1). The columns were operated in triplicate with one set containing raw (unfractionated) sand and the second containing sand with all particles <0.425 mm removed (fractionated sand) (Fig. 2). The raw sand has an effective size, uniformity coefficient and fineness modulus of D_{10} = 0.36, 2.3 and 1.67 respectively and D_{10} = 0.36, 2.0 and 2.78 respectively for the fractionated sand. To prevent

Table 1
Operational parameters of sand columns.

Sand type	Sand height (mm)	Sand weight (g)	HRT (h)	HLR (L·m^3 sand·day^{-1})
Raw	1450 ± 10.8 [1435–1460]	20,000 ± 0 [20000–20,000]	36.7 ± 0.3 [36.3–36.9]	191.2 ± 1.4 [189.9–193.1]
Fractionated	1444 ± 7.4 [1435–1453]	21,000 ± 408 [20500–21,500]	37.6 ± 0.3 [37.4–37.9]	191.9 ± 1.0 [190.8–193.1]

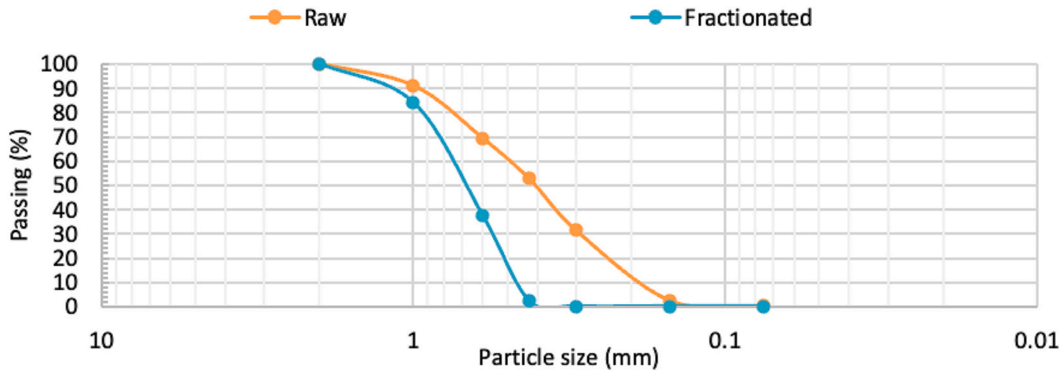

Fig. 2. Particle size distribution curves for raw and fractionated sand.

Table 2
Feeding schedule and physicochemical analysis of influent winery wastewater.

Period	Volume	COD	TN	TP	TPP	pH	Alk	Con
(day)	(L)	(mg·L^{-1})	(mg·L^{-1})	(mg·L^{-1})	(mg GAE·L^{-1})	(pH)	(mg HCO^{-}·L^{-1})	(µS·m^{-1})
Days 0–21[1]	4*	101	0.0	0.0	3.6	6.8	92	161
Days 21–42[1]	4*	206	0.0	0.0	2.4	6.8	67	153
Days 42–63[1]	8*	492	0.5	1.6	10.3	6.8	116	230
Days 63–84[1]	8*	961	2.6	5.8	16.4	6.6	134	438
Days 84–105[1]	13	1013	20.8	21.1	17.7	6.8	183	470
Days 105–126[2]	21	2538	73.1	9.2	55.3	5.6	409	1286
Days 126–130[3]	8	4681	89.3	29.6	38.2	4.9	311	1551

COD = chemical oxygen demand, TN = total nitrogen, TP = total phosphate, TPP = total poly-phenolics, GAE = gallic acid equivalents, Alk = Alkalinity, HCO = bicarbonate, Con = electrical conductivity, S = siemens, [1,2,3] = batch number of the winery wastewater.
* Wastewater diluted with filtered water.

sand washout and to ensure permanent saturation but unimpeded flow when required during operation, a complex sealing system consisting of gaskets, mesh screens, spigots, backing rings and ball valves were installed at the bottom outlet of each column. To increase the column lengths for sand HC measurements, spigots and backing rings were also installed at the top of the columns (Fig. 1B, C).

For the HC tests, the outlet piping was removed from the columns so that the flow was only restricted by the 50 mm ball valves. To increase the hydraulic head, temporary 2000 mm column lengths were joined to the top of the columns above the mesh and a stopwatch was used to measure the time it took for the water level to drop each 200 mm, with the final measurement being taken at a hydraulic head of 1520 mm. HC measurements for each column were conducted in triplicate.

For the performance evaluation experiments, each column was fed with WW. The hydraulic loading rate (HLR) was calculated in terms of the volume of sand within the column as previously described [18] (Table 1). The columns were fed via IVAC volumetric pumps (Model 597) at a rate of 2.4 L·day^{-1} with operational parameters as shown in Table 1. All the pumps were fed from the same holding vessel to ensure influent consistency.

Approximately 3 kg of sand was extracted from an operational BSR system containing functional biomass [21]. Distilled water was added to the extracted sand and sonicated. After the initial HC test, the columns were allowed to drain for 48 h then inoculated with 1 L of the supernatant fluid from the sonicated sand to the top of each column, which were then allowed to acclimate for 14 days.

After inoculation, starting at days 0, 21, 42, 63, 84, 105 and 126, the columns were fed with different batches of WW at 100 mL·h^{-1} for the allotted volume, sampled and outlet was closed till the next dosing (Table 2). During the start-up period (days 0 to 83), the WW was diluted with filtered water and the columns were fed with WW in increasing concentrations to allow the functional microbial communities to gradually acclimate to the WW. This ‘incremental priming’ has been shown to increase system performance in BSRs [28]. The systems were considered operational from day 84 (Table 2).

[] = Range, HRT = hydraulic retention time, HLR = hydraulic loading rate.

2.2. Sampling and characterisation of influent and effluent

From the third feeding period (days 42–63), effluent samples were taken over the last hour of each feeding period and analysed immediately. The pH was determined according to the manufacturer's instructions using a CyberScan pH 300 meter and appropriately calibrated pH probe PHWP300/02K (Eutech instruments, Singapore). The electrical conductivity (EC) was determined using a hand-held Oakton ECTestr 11+ multirange, cup-style pocket conductivity meter (Eutech Instruments, Singapore Cat No: 35665-35) with a range of 0 µS/m to 20 mS/m. The COD concentrations were determined using a Merck (Merck®, Whitehouse Station, USA) Spectroquant® Pharo instrument and Merck Spectroquant® cell tests (cat. no. 1.14895.0001, 1.14541.0001 and 1.14691.0001) according to manufactures instructions. The total phenolic concentrations were determined using the Folin-Ciocalteu micro method [29] using a Merck®Folin-Ciocalteu reagent (Cat No: 1.09001.0500). Total Alkalinity was measured using the Merck titrimetric method with titration pipette MQuant catalogue number (1.111109.0001), according to the manufacturer's instructions.

2.3. Characterisation of sand

The particle size distribution was performed using the SANS 3001 (Method AG1, PR5, AG21) by Cetlab, South Africa.

Fractionated samples of sand analysed by automated scanning electron microscopy using a FEI QEMSCAN® (Quantitive Evaluation of Minerals by SCANning Electron Microscopy) instrument (Thermo Fisher Scientific, Waltham, USA) and iDiscover™ software. The roundness and aspect ratios of the different mineral fractions determined using the iDiscover™ software were used to compare the shapes and sizes of

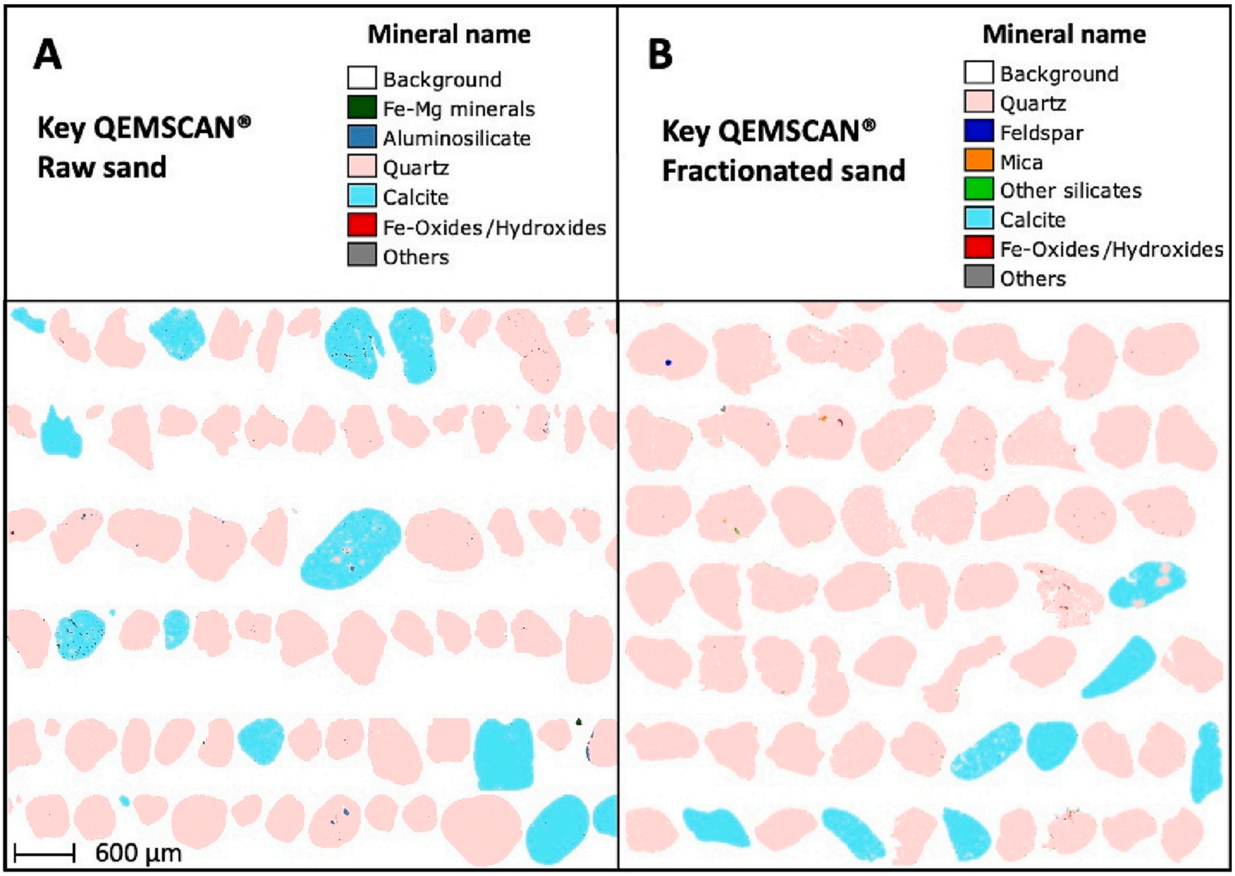

Fig. 3. Computer generated (QEMSCAN®) images of the raw (A) and fractionated (B) sand particles.

particles with different mineral composition as previously described [23,30].

3. Results and discussion

3.1. Hydraulic performance

The saturated HC is the intrinsic value which describes the rate at which fluid moves though a saturated porous media and is affected by the porosity of the medium, particle packing, particle size [23] and uniformity of the particles [22]. In this study, indices obtained via QEMSCAN® were used to compare the morphologies of the raw and fractionated sand [23,30]. For the raw sand, the quartz and calcite contributions were 81.3 % (wt.wt.) and 17.6 % (wt.wt.), while for the fractionated sand, they were 74.0 % (wt.wt.) and 9.6 % (wt.wt.) respectively. Computer generated images of the morphology and mineralogy of the raw and fractionated sand obtained using via QEMSCAN are shown in Fig. 3. Additional information of the character of the raw sand can be found in literature [22,23].

It was previously established that the HC of the sand with the smaller fractions (>0.6 mm) removed exhibited a significantly higher ($p < 0.05$) HC (2.75 ± 0.02 mm·s^{-1}) than the raw sand (0.41 ± 0.10 mm·s^{-1}), but the relative losses in HC due to the formation of functional biomass were not determined [19,22]. In this study, the HC results before and after biomass formation were very similar to those obtained in an earlier experiment conducted using columns containing a batch of sand from the same quarry site fed with synthetic WW for 14 weeks [22]. The initial comparative HC values of the raw sand batches were: 0.28 ± 0.05 mm·s^{-1} (this study) and 0.284 mm·s^{-1} [22], with respective reductions in HC due to the growth of functional biomass of 52.3 ± 6 % and 52 %.

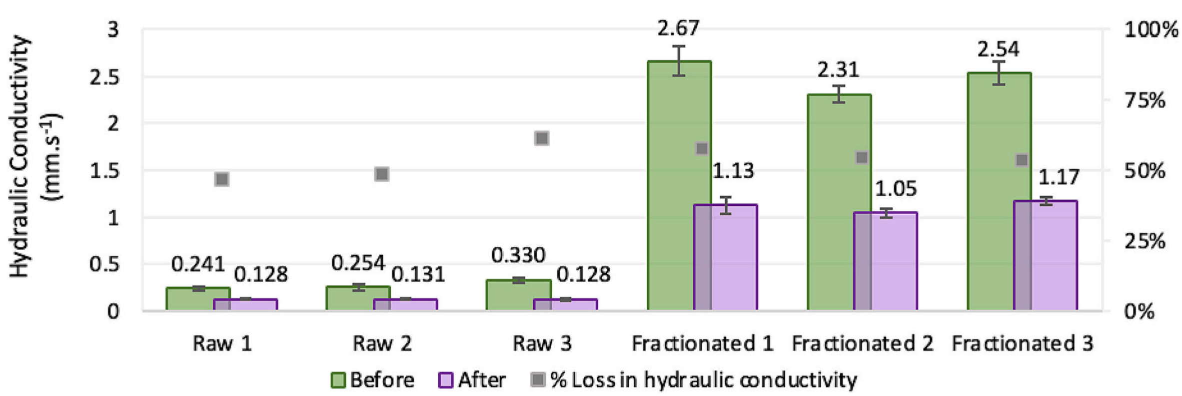

Fig. 4. The hydraulic conductivity of raw and fractionated sand measured in experimental columns before and after feeding with winery wastewater.

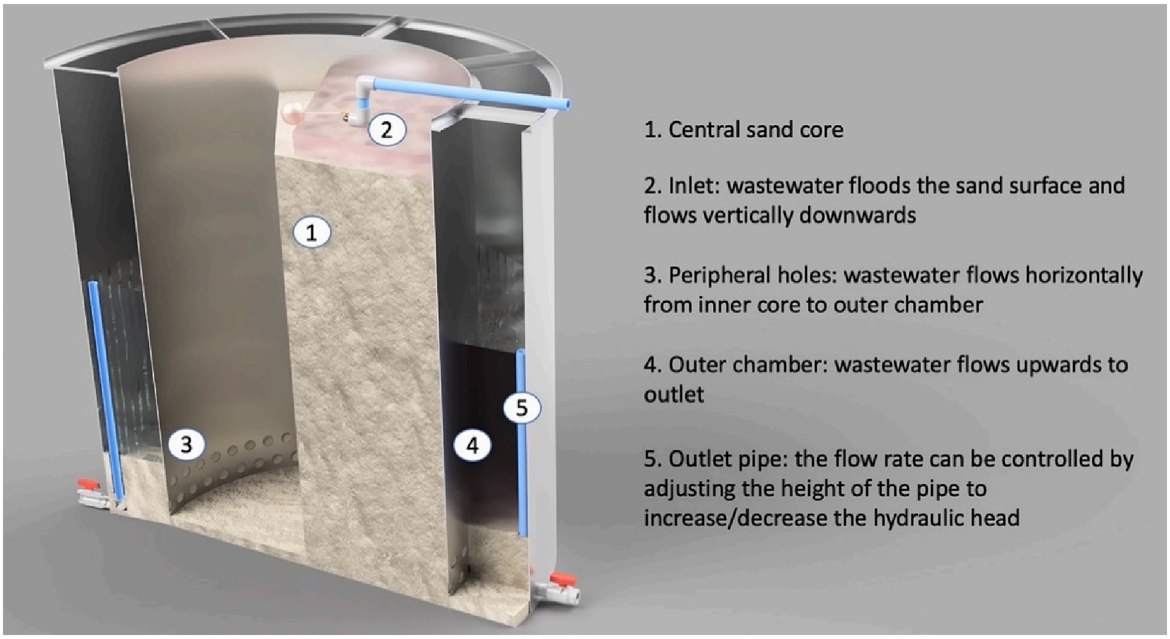

Fig. 5. Cross-section of a novel biosand filter module.
(Adapted from Holtman et al. [21]).

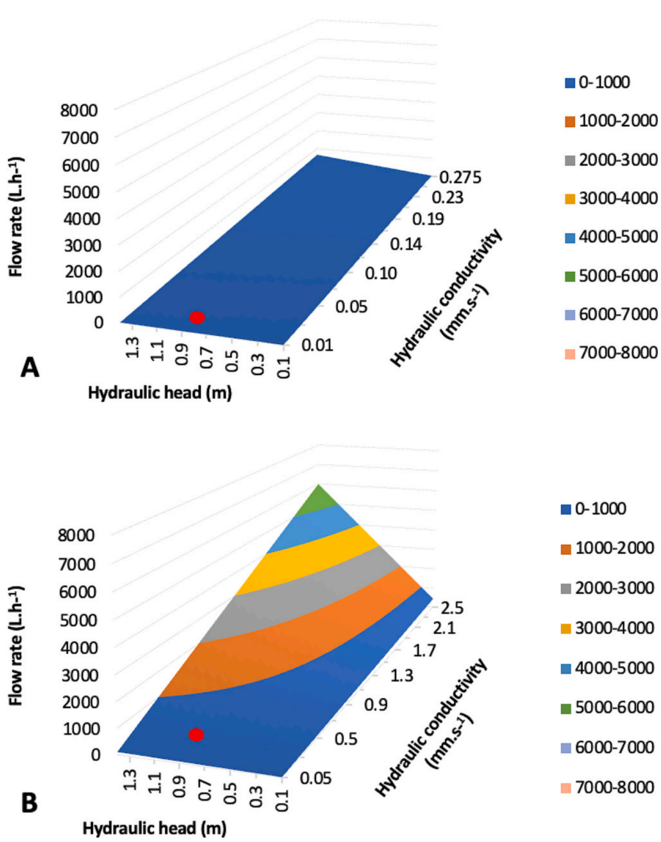

Fig. 6. Potential ranges of flow rates that can be achieved in biosand reactors containing raw (A) and fractionated (B) sand before and after biomass accumulation. The theoretical flow rates, used in Table 3, after biomass accumulation are denoted with a red circle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For the fractionated sand, the initial HC of 2.50 ± 0.20 mm·s^{-1} reduced by 55.4 ± 2 % after feeding with WW for 19 weeks, but the HC (average 1.15 ± 0.081 mm·s^{-1}) was still >4 fold higher than the initial HC of the raw sand (Fig. 4).

The HC results were applied to a pilot BSR system with a novel design [21] shown in Fig. 5. In the system, pre-settled WW is applied to the surface of the BSR modules and flows passively through the system as indicated in the diagram. The adjustable outlets allow the HLR to be manipulated by changing the hydraulic head to the maximum rate dictated by the HC. It was found that the range of possible flow rates was considerably greater when using fractionated sand in comparison to raw sand in the BSR modules (Fig. 6).

When the pilot system was operated with raw sand and a hydraulic head of 0.8 m, the maximum achievable flow rate during the crush season was <250 L·d^{-1} per module [21]. By applying the HC results obtained in the column experiments containing fractionated sand, it was calculated that this rate could theoretically be increased to 114,681 L·d^{-1} (before) and 5455 L·d^{-1} (after) biomass accumulation during the crush season. This would reduce the HRT for the reactor module to 17.8 h during the crush season (Fig. 6). In reality, the maximum operational flow, with a hydraulic head of 0.8 m, would be limited to 8102 L·d^{-1} which equates to a HLR of 3212 L·m^{-3}of sand.d^{-1} in order to provide sufficient HRT (12h) for bioremediation of the WW. In other words, when calculating the WW volume generated/tonne of grapes crushed previously formulated [31], one BSR module containing fractionated sand would be required for wineries that crush 547 t or 329 t of grapes, respectively, producing 50 % or 80 % of their WW during the crush season. In comparison, a single BSR module would be capable of treating the WW from wineries crushing approximately three times as many grapes when applying the WW generation volume of 3.05 m^3 WW/tonne of grapes crushed formulated by another group of researchers [32].

3.2. Remediation performance of biosand filters with fractionated and raw sand

3.2.1. Organic removal rates

Due to the organic nature of WW, the organic fraction was measured using COD as a proxy [6]. It has been conclusively established that BSRs containing raw sand are capable of significantly reducing the COD of

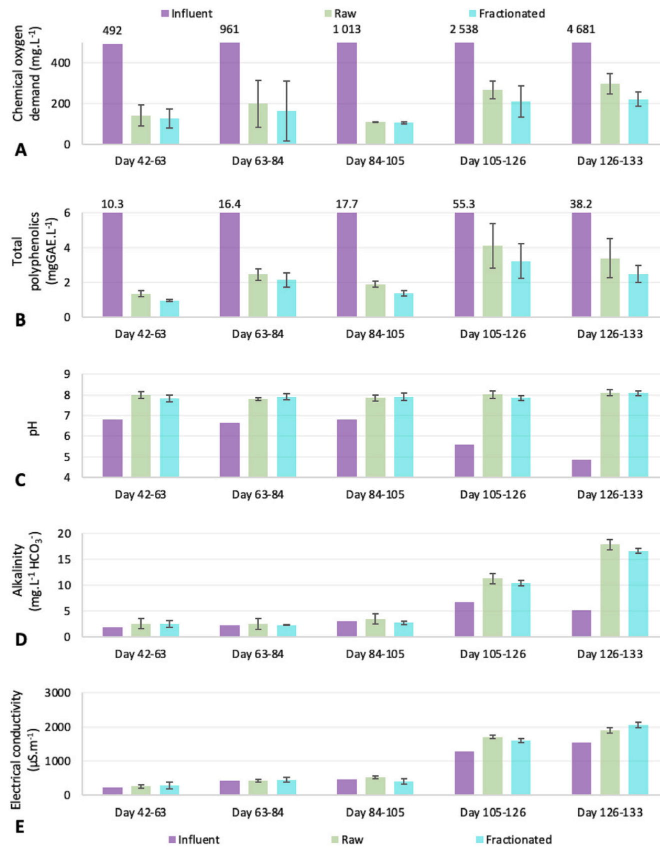

Fig. 7. Results of A) chemical oxygen demand, B) total polyphenolics, C) pH, D) alkalinity and E) electrical conductivity of influent and samples taken from experimental columns containing raw and fractionated sand.

WW, including the concentrations of polyphenolics [18,21,33,34]. A pilot system containing raw sand was able to treat WW at higher organic loading rates (279 g COD·m^{-3} of sand·day^{-1}) with a smaller spatial footprint than reported for other passive systems (constructed/treatment wetlands) [21].

In this study, the use of fractionated sand had a positive influence, not only on hydraulic performance, but on COD removal efficiency (Fig. 7A). The COD removal efficiencies in the columns containing raw and fractionated sand ranged from 71 % to 94 %, and 74 % to 95 %, respectively. For the final sampling instance (with the most concentrated WW), the organic removal efficiency in the columns containing fractionated sand was 95 % (±1 %) with influent and effluent concentrations of 4681 mg·L^{-1} and 222 mg·L^{-1} (±43), respectively. This was comparable with the 94 % (±1 %) organic removal efficiency and effluent concentration of 298 mg·L^{-1} (±61) obtained with the raw sand (Fig. 7A). The trend continued with the removal of total polyphenolics with the fractionated sand columns having slightly higher removal efficiencies (87 % to 94 %) than the raw sand columns (87 % to 93 %) with influent values ranging from 10.4 to 55.3 mg GAE·L^{-1} (Fig. 7B).

3.2.2. Neutralization of acidic winery wastewater

Winery wastewater is typically acidic, which may have a negative impact on the receiving environment. It has been established that BSRs are capable of neutralizing acidic WW and increasing the sodium adsorption ratio (SAR) [18]. The main pH adjustment mechanism in BSRs is via abiotic dissolution of calcite [19,23], but biotic mechanisms are also involved [19]. It is possible that some calcite solubilises and then re-precipitates when the WW flows through BSRs and becomes less acidic. However, QEMSCAN results have shown that no other Ca-based minerals such as anhydrite or gypsum are formed [19,23]. The longevity of BSR systems in terms of calcite dissolution capacity is beyond the projected life of the systems, with a lifespan of 37 years being calculated using data from column and in-situ experiments for systems containing approximately 10 % calcite. Furthermore, it has been shown that loss of calcite particles does not have a deleterious effect ($p > 0.05$) on the HC [23].

In this study, the pH in the final effluent from the columns containing both raw and fractionated sand was slightly alkaline, with no significant ($p > 0.5$) differences between effluent values. In the final sampling instance, the pH of the acidic WW increased from 4.86 to 8.13 (±0.17) and 8.10 (±0.14) after treatment in the columns containing raw and fractionated sand, respectively (Fig. 7C). There were temporal changes over the sampling period for both total alkalinity and EC of the effluent WW (Fig. 7D, E). Both of these parameters increased when the columns were fed with more concentrated WW with lower pH values, supporting previous results that showed that calcite dissolution increases with decreases in acidity [19,23]. Overall, the result showed that fractionation of sand did not have a negative impact on the WW pH neutralization mechanisms.

Table 3
Comparison of hydraulic and organic loading rates of biological sand reactors and other passive systems treating winery wastewater.

HLR mm·d^{-1}	HLR_{Vol} L·m^{-3}·d^{-1}	OLR_{Vol} g COD·m^3·d^{-1}	Ref
14.6*	41.7*	32.9 to 124.5	[35]
7.3*	20.8*	16.4 to 62.1	
14	14 (VF)	152* (VF)	[36,37]
24.8	43–82 (HF_1)	54* (HF_1)	
36.3	22–41 ($HF_{2,3}$)	27* ($HF_{2,3}$)	
77–215	55–154* (VF)	31–333* (VF)	[25]
13–36	43–120* (HF_1)	12–183* (HF_1)	
13–36	22–60* ($HF_{2,3}$)	6.0–92* ($HF_{2,3}$)	
34	28*	37–176*	[38–40]
333*	150	152	[18,22]
23	1) 25*	1) 350*	[41,42]
45	2) 50*	2) NG	
78.3	57.0	260.4	[21] Year 1
206.5	150.3	322.9	[21] Year 2
425	223	447#	This study: raw sand after biomass accumulation during the crush season
4110	2163	4326#	This study: fractionated sand after biomass accumulation during the crush season

HLR = hydraulic (surface) loading rate, HF = horizontal (subsurface) flow, VF = vertical (subsurface) flow.
* Calculated, HLR_{Vol} = volumetric hydraulic loading rate, OLR_{Vol} = volumetric organic loading rate.
# Theoretical value with assumed influent of 2000 mg (COD).L^{-1} (Adapted from [21]).

3.2.3. Comparison of hydraulic and organic loading of biosand reactors with other passive treatment systems treating winery wastewater

The theoretical organic loading rates (OLR) and HLRs loading rates measured in the pilot BSR system containing raw sand were notably higher than in other passive systems treating WW, translating into a comparatively lower spatial footprint [21]. Based on the results obtained from this study when using fractionated sand and applying a hydraulic head of 0.8 m (Fig. 5), the theoretical OLRs and HLRs after biomass accumulation during the crush season were typically an order of magnitude higher than in other systems, including the pilot BSR system containing raw sand (Table 3).

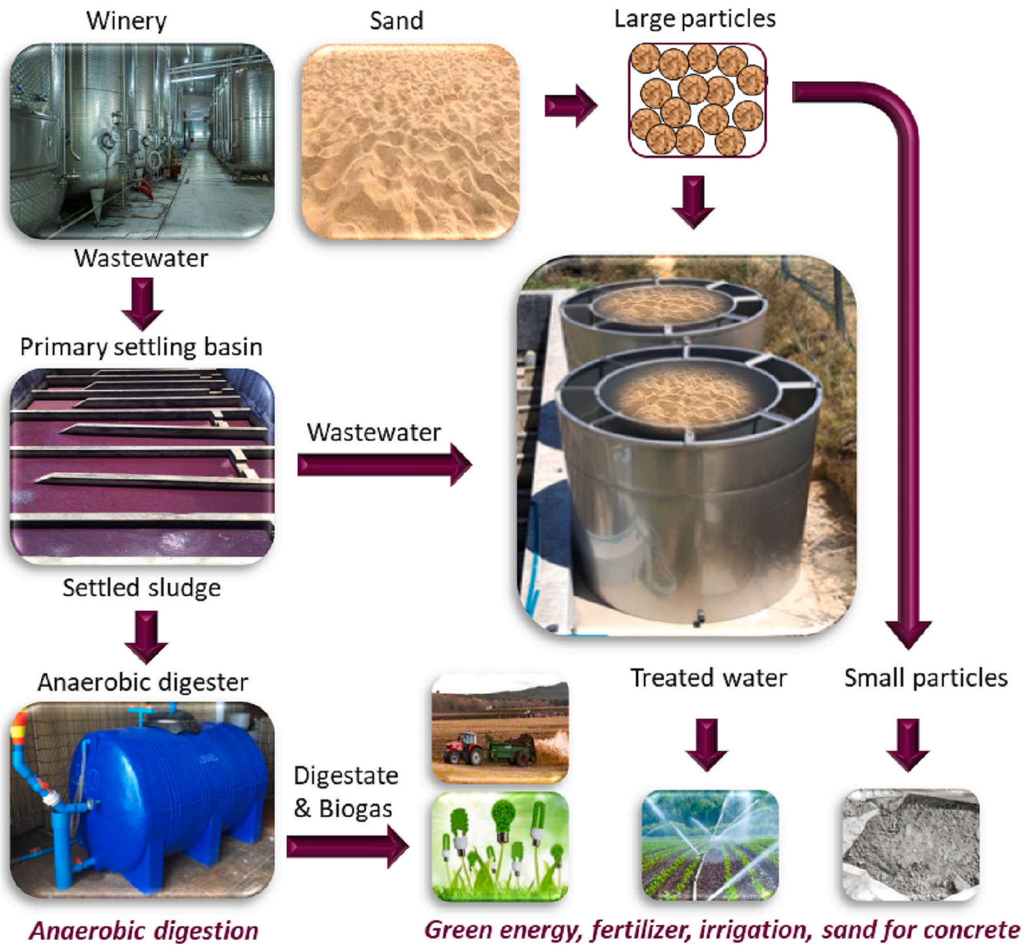

Fig. 8. Schematic of proposed 'zero waste' biosand reactor-based system for valorisation of winery wastewater.

Table 4
Design criteria for biosand reactor systems treating winery wastewater and/or digesting primary winery wastewater sludge.

Parameter	Units	Tonnes of grapes crushed							
		10	100	500	1000	2000	5000	10,000	20,000
Calculated volume of wastewater produced yearly*	$m^3 \cdot year^{-1}$	37	313	1387	2633	4996	11,654	22,116	41,971
Produced 80 % of wastewater in crush#	$m^3 \cdot day^{-1}$	0.3	2.7	12	23	43	100	190	361
Produced 50 % of wastewater in crush#	$m^3 \cdot day^{-1}$	0.2	1.7	7.5	14	27	63	119	226
Number of 5.6 m^3 BSR modules required for 80 % wastewater in crush#	Each	1	1	2	3	6	13	24	45
Number of 5.6 m^3 BSR modules required for 50 % wastewater in crush#	Each	1	1	1	2	4	8	15	28
Calculated volume of sludge produced per year	$kg \cdot year^{-1}$	84	709	3137	5953	11,297	26,349	50,004	94,896
Produced 80 % of sludge in crush#	$kg \cdot day^{-1}$	0.7	6.1	27	51	97	227	430	816
Produced 50 % of sludge in crush#	$kg \cdot day^{-1}$	0.5	3.8	17	32	61	142	269	510
Calculated volume of methane produced per year	ML CH_4	11	92	405	769	1460	3406	6464	12,266
Produced 80 % of methane in crush#	ML $CH_4 \cdot day^{-1}$	0.1	0.8	3.5	6.6	13	29	56	106
Produced 50 % of methane in crush#	ML $CH_4 \cdot \cdot day^{-1}$	0.1	0.5	2.2	4.1	7.9	18	35	66
Potential power produced per year	kW	23	192	851	1616	3066	7152	13,574	25,760
Produced 80 % of electricity in crush#	$kW \cdot day^{-1}$	0.2	1.7	7.3	14	26	62	117	222
Produced 50 % of electricity in crush#	$kW \cdot day^{-2}$	0.1	1.0	4.6	8.7	16	38	73	138

* Calculated using Sheridan 2003 [31]
# Converted to a daily flow rate for a winery producing ether 50 % or 80 % of their wastewater during a 3 month crush season, ML = Mega litres.

3.3. Sustainable and circular economy approach for valorisation of winery wastewater: towards zero waste for wineries

Circular economy principles have been envisaged, evaluated, and/or applied in the wine industry for a range of products, services, and solid wastes/by-products. These include wine packaging [43], multiple external and internal stakeholder engagements and activities [44], biorefineries for the extraction of tartrates, antioxidants and other value-added products from grape pomace and lees [7,8], and the use of solids wastes for animal feed and composting.

Passive systems such as constructed/treatment wetlands and BSRs are sustainable options for remediation of WW [17,18,20,21,45]. Building on the results obtained from previous studies, a circular economy and zero waste model for WW remediation and valorisation based on the use of BSRs is proposed (Fig. 8). The intention is to promote the design and implementation of integrated sustainable systems for reuse and recycling of WW and primary winery wastewater sludge (PWWS) in order to contribute to minimizing waste formation and maximizing resource recovery in wineries [46].

In comparison to other passive treatment systems, BSRs containing fractionated sand (particles >0.425 mm) are envisaged to have even smaller spatial footprints and higher OLRs than previous systems containing raw sand (Section 3.2.2. [19]). As alluded to in Section 3.1, it is feasible that these 'new' BSR systems can be implemented at wineries crushing around 547 t of grapes and generating 1507 m^3 of WW or less per annum, taking into account 50 % peak flows during the crush period. This amount of WW can theoretically be treated using just one 5.6 m^3 BSR module containing 2.9 m^3 of sand. The WW treatment capacity can be increased by adding additional modules where practically possible (Table 4). Alternatively, the size of the modules may be increased. While sand containing larger particles is more desirable for use in BSRs, the cost of fractionating the sand can be offset by using the finer sand fractions, for example, SCC in the building industry [24].

Remediation of WW using BSRs renders it suitable for irrigation purposes, reducing water consumption which is important in water-stressed wine-producing areas such as South Africa, Australia and California, USA [47,48].

Before WW is remediated in BSRs, the solids are removed using primary settling. In a survey conducted in South Africa, 25 % of wineries indicated that they use commercial companies to remove PWSS and dump it in landfills. This is an economic and environmental burden on the industry and is more likely to take place in medium and larger wineries than smaller wineries. In addition, medium-large wineries tend to dispose of PWWS more frequently than smaller wineries [49,50]. In another study, it was found that the Na in WW does not partition into the PWWS, and that it is amendable to anaerobic digestion (AD), generating up to 206 ± 2.7 mL CH_4/gVS_{added} [5]. These results suggest that it may be feasible for biogas generated from co-digestion of PWWS and other available organic substrates to be used as part of a renewable energy mix in wineries [5,51]. In addition, it was shown that the digestate from AD of PWWS has potential as an organic agricultural fertilizer as it contains micronutrients and high concentrations of N (21.5 to 27.7 g/kg dry weight) and C (229 to 277 g/kg dry weight) [5].

In summary, based on the results of this research and previous findings, the a zero waste model is proposed which consists of the following objectives: (i) to fractionate sand and use the fraction with larger particles (>0.425 mm) in BSRs and the smaller fraction in high performance concrete i.e. SCC, (ii) to remediate WW in BSRs and use the treated effluent for irrigation, (iii) to digest PWWS and use the biogas for energy and the digestate as an agricultural fertilizer (Fig. 8). Data for different size categories of wineries generating different volumes of WW are provided in (Table 4).

The volume and character of WW is incumbent on cellar practices and differs from winery to winery [6,32,52]. In most cases, the highest volume of WW (up to 80 %) is usually generated during the standard three-month crush period, but this figure can vary quite widely. For example, some wineries do not crush while other do not bottle on site and a number of wineries have bottling facilities which will result in greatly different flow rates with the latter generating considerable quantities outside the crush season [17,53,54] Table 4 provides data that can assist practitioners to capacitate integrated BSR systems for different sized wineries based on the amount of grapes crushed per annum and maximum peak flows (50–80 % during crush period). The amount of methane generated can be estimated using the volume of total sludge (TS) 2261 mg $TS \cdot L^{-1}$ of wastewater [49], in press, converting the TS to volatile solids (VS) TS:VS ratio of 0.675 and VF to methane 191.5 $mLCH_4 \cdot gVS^{-1}$ [5]. In addition the average calorific value of 6 $kWh \cdot m^3$ and a conversion efficiency of 35 % was used to calculate the electricity generation [56]. For example, a winery crushing 1000 t of grapes would require 3 BSR modules with fractionated sand, if 80 % of the WW is produced in the crush. The sludge would potentially yield 1266 kWh of electricity from the methane.

4. Conclusion

To conclude, a circular economy approach for the treatment and valorisation of waste gives a purpose and a value to waste. The BSR system containing raw sand has a proven track record in terms of treatment of WW. Previously, a drawback was associated with reduction in HC due to the accumulation of functional biomass during the crush season that reduced the BSR treatment capacity to below the design limit. This study showed that the HC and flow rate can be increase 9-fold by using fractionated sand with the smaller particles removed. With the experimental test setup, BSR columns containing fractionated sand also showed excellent organic removal efficiencies and increased the pH of acidic WW. With a zero-waste model, it is suggested that the larger fraction of sand (>0.425 mm) is used in BSRs and the smaller fraction in high performance concretes. The solid fraction of WW can be anaerobically digested producing biogas which may be used for energy and digestate used as an agricultural fertilizer. The quality of the remediated WW is acceptable for irrigation purposes.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pamela J Welz reports financial support was provided by Wine Industry Network for Expertise and Technology.

Data availability

Data will be made available on request.

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References

[1] Wei R. Teng, N. Chen, Ding Y. Ting, L. Wang, Liu Y. Hui, Gao F. Fei, et al., Correlations between microbiota with physicochemical properties and volatile compounds during the spontaneous fermentation of Cabernet Sauvignon (Vitis vinifera L.) wine, Lwt. December 2021 (163) (2022), 113529 available from, https://doi.org/10.1016/j.lwt.2022.113529. available from.
[2] P.T. Liu, L. Lu, C.Q. Duan, G.L. Yan, The contribution of indigenous non-Saccharomyces wine yeast to improved aromatic quality of cabernet sauvignon wines by spontaneous fermentation, Lwt. 71 (2016) 356–363, available from, https://doi.org/10.1016/j.lwt.2016.04.031. available from.
[3] L. Liang, Y. Ma, Z. Jiang, F.E. Sam, S. Peng, M. Li, et al., Dynamic analysis of microbial communities and flavor properties in Merlot wines produced from inoculation and spontaneous fermentation, Food Res. Int. December 2022 (164) (2023), 112379 available from, https://doi.org/10.1016/j.foodres.2022.112379. available from.
[4] Y. Liu, S. Rousseaux, R. Tourdot-Maréchal, M. Sadoudi, R. Gougeon, P. Schmitt-Kopplin, et al., Wine microbiome: a dynamic world of microbial interactions, Crit. Rev. Food Sci. Nutr. 57 (4) (2017) 856–873, available from, https://doi.org/10.1080/10408398.2014.983591. available from.
[5] W.M. Kaira, E. Kimpiab, A.B. Mpofu, G.A. Holtman, A. Ranjan, P.J. Welz, Anaerobic digestion of primary winery wastewater sludge and evaluation of the character of the digestate as a potential fertilizer, Biomass Convers Bioref. (2022), https://doi.org/10.1007/s13399-022-03087-8 available from.
[6] P.J. Welz, G. Holtman, R. Haldenwang, M. Le Roes-Hill, M. Roes-hill, Characterisation of winery wastewater from continuous flow settling basins and waste stabilisation ponds over the course of 1 year: implications for biological wastewater treatment and land application, Water Sci. Technol. 74 (9) (2016) 2036–2050, available from, https://doi.org/10.2166/wst.2016.226. available from.
[7] M. Perra, J. Lozano-Sánchez, F.J. Leyva-Jiménez, A. Segura-Carretero, J.L. Pedraz, G. Bacchetta, et al., Extraction of the antioxidant phytocomplex from wine-making by-products and sustainable loading in phospholipid vesicles specifically tailored

for skin protection, Biomed. Pharmacother. 142 (June) (2021), https://doi.org/10.1016/j.biopha.2021.111959 available from.

[8] M.M. Contreras, J.M. Romero-García, J.C. López-Linares, I. Romero, E. Castro, Residues from grapevine and wine production as feedstock for a biorefinery, Food Bioprod. Process. 134 (2022) 56–79, available from, https://doi.org/10.1016/j.fbp.2022.05.005. available from.

[9] N. Ngwenya, C. Gaszynski, D. Ikumi, A review of winery wastewater treatment: a focus on UASB biotechnology optimisation and recovery strategies, J. Environ. Chem. Eng. 10 (4) (2022), 108172 available from, https://doi.org/10.1016/j.jece.2022.108172. available from.

[10] R. Sirohi, A. Tarafdar, S. Singh, T. Negi, V.K. Gaur, E. Gnansounou, et al., Green processing and biotechnological potential of grape pomace: current trends and opportunities for sustainable biorefinery, Bioresour. Technol. 314 (May) (2020), 123771 available from, https://doi.org/10.1016/j.biortech.2020.123771. available from.

[11] K.P.M. Mosse, A.F. Patti, E.W. Christen, T.R. Cavagnaro, Winery wastewater inhibits seed germination and vegetative growth of common crop species, J. Hazard. Mater. 180 (1–3) (2010) 63–70, available from, https://doi.org/10.1016/j.jhazmat.2010.02.069. available from.

[12] C.L. Howell, P.A. Myburgh, S. Africa, I.S. Africa, I.S. Africa, Management of winery wastewater by re-using it for crop irrigation — a review, S. Afr. J. Enol Vitic. 39 (1) (2018) 116–131, available from, 10.21548/39-1-2475. available from.

[13] Mosse KPM, Patti AF, Smernik RJ, Christen EW, Cavagnaro TR. Physicochemical and microbiological effects of long- and short-term winery wastewater application to soils. J. Hazard. Mater. 2012;201–202:219–28. available from, doi:https://doi.org/10.1016/j.jhazmat.2011.11.071.

[14] R. Devesa-Rey, X. Vecino, J.L. Varela-Alende, M.T. Barral, J.M. Cruz, A.B. Moldes, Valorization of winery waste vs. the costs of not recycling, Waste Manag. 31 (11) (2011) 2327–2335, available from, https://doi.org/10.1016/j.wasman.2011.06.001. available from.

[15] Giacobbo A, Meneguzzi A, Bernardes AM, de Pinho MN. Pressure-driven membrane processes for the recovery of antioxidant compounds from winery effluents. J. Clean. Prod. 2017;155:172–8. available from, doi:https://doi.org/10.1016/j.jclepro.2016.07.033.

[16] Ioannou LA, Puma GL, Fatta-Kassinos D. Treatment of winery wastewater by physicochemical, biological and advanced processes: a review. J. Hazard. Mater. 2015;286:343–68. available from, doi:https://doi.org/10.1016/j.jhazmat.2014.12.043.

[17] A.E. Mader, G.A. Holtman, P.J. Welz, Treatment wetlands and phyto-technologies for remediation of winery effluent: challenges and opportunities, Sci. Total Environ. 807 (2022), 150544 available from, https://doi.org/10.1016/j.scitotenv.2021.150544. available from.

[18] G.A. Holtman, R. Haldenwang, P.J. Welz, Biological sand filter system treating winery effluent for effective reduction in organic load and pH neutralisation, J. Water Process Eng. 25 (July) (2018) 118–127, available from, https://doi.org/10.1016/j.jwpe.2018.07.008. available from.

[19] G.A. Holtman, R. Haldenwang, P.J. Welz, Calcite dissolution and bioneutralization of acidic wastewater in biosand reactors, Water. 14 (21) (2022), 3482 available from, https://doi.org/10.3390/w14213482. available from.

[20] P.J. Welz, M. le Roes-Hill, Biodegradation of organics and accumulation of metabolites in experimental biological sand filters used for the treatment of synthetic winery wastewater: a mesocosm study, J. Water Process Eng. 3 (C) (2014) 155–163, available from, https://doi.org/10.1016/j.jwpe.2014.06.007. available from.

[21] G.A. Holtman, R. Haldenwang, P.J. Welz, Comparison of continuous and pulse mode of operation of pilot biosand reactors treating winery effluent, Ecol. Eng. 182 (May) (2022), 106706 available from, https://doi.org/10.1016/j.ecoleng.2022.106706. available from.

[22] P.J. Welz, W. Mbasha, I. Smith, G. Holtman, G. Terblanche, M. Le Roes-Hill, et al., The influence of grain physicochemistry and biomass on hydraulic conductivity in sand-filled treatment wetlands, Ecol. Eng. 116 (February) (2018) 21–30, available from, https://doi.org/10.1016/j.ecoleng.2018.02.017. available from.

[23] G.A. Holtman, R. Haldenwang, P.J. Welz, Effect of particle character and calcite dissolution on the hydraulic conductivity and longevity of biosand filters treating winery and other acidic effluents, Water. 14 (17) (2022) 2603, available from, https://doi.org/10.3390/w14172603. available from.

[24] P. Nimodiya, H. Patel, Experimental investigation of effect of sand fines on properties experimental investigation of effect of sand fines on properties of self compacting concrete, J. Emerg. Technol. Innov. Res. 5 (9) (2018), https://doi.org/10.1729/Journal.18470 available from.

[25] L. Serrano, Varga D. De, I. Ruiz, M. Soto, Winery wastewater treatment in a hybrid constructed wetland, Ecol. Eng. 37 (5) (2011) 744–753, available from, https://doi.org/10.1016/j.ecoleng.2010.06.038. available from.

[26] H. Wu, J. Zhang, H.H. Ngo, W. Guo, Z. Hu, S. Liang, et al., A review on the sustainability of constructed wetlands for wastewater treatment: design and operation, Bioresour. Technol. 175 (2015) 594–601, available from, https://doi.org/10.1016/j.biortech.2014.10.068. available from.

[27] P.J. Welz, J.-B. Ramond, D.A. Cowan, S.G. Burton, M. le Roes-Hill, Minor differences in sand physicochemistry lead to major differences in bacterial community structure and function after exposure to synthetic acid mine drainage. Biotechnol, Bioprocess Eng. 19 (2) (2014) 211–220, available from, https://doi.org/10.1007/s12257-013-0454-6. available from.

[28] P.J. Welz, J.B. Ramond, D.A. Cowan, A. Prins, S.G. Burton, Ethanol degradation and the benefits of incremental priming in pilot-scale constructed wetlands, Ecol. Eng. 37 (10) (2011) 1453–1459, available from, https://doi.org/10.1016/j.ecoleng.2011.03.009. available from.

[29] K. Slinkard, V.L. Singleton, Total phenol analysis: automation and comparison with manual methods [Sweet wines]. Vol. v. 28, Am. J. Enol. Vitic (USA) 28 (January) (1977) 49–55, https://doi.org/10.5344/ajev.1977.28.1.49.

[30] L. Little, M. Becker, J. Wiese, A.N. Mainza, Auto-SEM particle shape characterisation: investigating fine grinding of UG2 ore, Miner. Eng. 82 (2015) 92–100, available from, https://doi.org/10.1016/j.mineng.2015.03.021. available from.

[31] C.M. Sheridan, A Critical Process Analysis of Wine Production to Improve Cost Efficiency, Wine Quality and Environmental Performance, University of Stellenbosch, 2003.

[32] D. Bolzonella, M. Papa, C. Da Ros, L. Anga Muthukumar, D. Rosso, Ros C. Da, et al., Winery wastewater treatment: a critical overview of advanced biological processes, Crit. Rev. Biotechnol. 39 (4) (2019) 489–507, available from, https://doi.org/10.1080/07388551.2019.1573799. available from.

[33] P.J. Welz, J.B. Ramond, D.A. Cowan, S.G. Burton, Phenolic removal processes in biological sand filters, sand columns and microcosms, Bioresour. Technol. 119 (2012) 262–269, available from, https://doi.org/10.1016/j.biortech.2012.04.087. available from.

[34] P. Welz, J.-B. Ramond, D. Cowan, I. Smith, Z. Palmer, R. Haldenwang, et al., Treatment of Winery Wastewater in Unplanted Constructed Wetlands, 2015. WRC Report No 2104/1/14.

[35] C.S. Akratos, T.I. Tatoulis, A.G. Tekerlekopoulou, Biotreatment of winery wastewater using a hybrid system combining biological trickling filters and constructed wetlands, Appl. Sci. 10 (2) (2020) 619, available from, https://doi.org/10.3390/app10020619. available from.

[36] D. De La Varga, I. Ruiz, M. Soto, Winery wastewater treatment in subsurface constructed wetlands with different bed depths, Water Air Soil Pollut. 224 (4) (2013), https://doi.org/10.1007/s11270-013-1485-5 available from.

[37] De la Varga D, Díaz MA, Ruiz I, Soto M. Avoiding clogging in constructed wetlands by using anaerobic digesters as pre-treatment. Ecol. Eng. 2013;52:262–9. available from, doi:https://doi.org/10.1016/j.ecoleng.2012.11.005.

[38] H.L. Shepherd, M.E. Grismer, G. Tchobanoglous, Treatment of high-strength winery wastewater using a subsurface-flow constructed wetland, Water Environ. Res. 73 (4) (2001) 394–403, available from, https://doi.org/10.2175/106143001X139434. available from.

[39] M.E. Grismer, M. Tausendschoen, H.L. Shepherd, Hydraulic characteristics of a subsurface flow constructed wetland for winery effluent treatment, Water Environ. Res. 73 (4) (2001) 466–477, available from, https://doi.org/10.2175/106143001x139524. available from.

[40] H.L. Shepherd, G. Tchobanoglous, M.E. Grismer, Time-dependent retardation model for chemical oxygen demand removal in a subsurface-flow constructed wetland for winery wastewater treatment, Water Environ. Res. 73 (5) (2001) 597–606, available from, https://doi.org/10.2175/106143001x143321. available from.

[41] Mulidzi AR, Africa S. Winery wastewater treatment by constructed wetlands and the use of treated wastewater for cash crop production. Water Sci. Tech., 56(2), 103–109. doi:https://doi.org/10.2166/wst.2007.478.

[42] A.R. Mulidzi, Winery and distillery wastewater treatment by constructed wetland with shorter retention time, Water Sci. Technol. 61 (10) (2010) 2611–2615, available from, https://doi.org/10.2166/wst.2010.206. available from.

[43] C. Ferrara, V. Migliaro, F. Ventura, G. De Feo, An economic and environmental analysis of wine packaging systems in Italy: a life cycle (LC) approach, Sci. Total Environ. 857 (October 2022) (2023), 159323 available from, https://doi.org/10.1016/j.scitotenv.2022.159323. available from.

[44] R. Mura, F. Vicentini, L.M. Botti, M.V. Chiriacò, Economic and environmental outcomes of a sustainable and circular approach: case study of an Italian wine-producing firm, J. Bus. Res. 154 (February 2021) (2023), https://doi.org/10.1016/j.jbusres.2022.113300 available from.

[45] M. Sánchez, O.G. Gonzalo, S. Yáñez, I. Ruiz, M. Soto, Influence of nutrients and pH on the efficiency of vertical flow constructed wetlands treating winery wastewater, J. Water Process Eng. 42 (2021) 102103, available from, https://doi.org/10.1016/j.jwpe.2021.102103. available from.

[46] J. Chen, L. Dai, D. Mataya, K. Cobb, P. Chen, R. Ruan, Enhanced sustainable integration of CO_2 utilization and wastewater treatment using microalgae in circular economy concept, Bioresour. Technol. 366 (October) (2022), 128188 available from, https://doi.org/10.1016/j.biortech.2022.128188. available from.

[47] K.L. Christ, R.L. Burritt, Critical environmental concerns in wine production: an integrative review, J. Clean. Prod. 53 (2013) 232–242, available from, https://doi.org/10.1016/j.jclepro.2013.04.007. available from.

[48] S.A.A.A.N. Almuktar, S.N. Abed, M. Scholz, Wetlands for wastewater treatment and subsequent recycling of treated effluent: a review, Environ. Sci. Pollut. Res. 25 (24) (2018) 23595–23623, available from, https://doi.org/10.1007/s11356-018-2629-3. available from.

[49] Flores L, García J, Pena R, Garfí M. Constructed wetlands for winery wastewater treatment: a comparative life cycle assessment. Sci. Total Environ. 2019;659: 1567–76. available from, doi:https://doi.org/10.1016/j.scitotenv.2018.12.348.

[50] P. Welz, W. Kaira, N. Deepnarain, A. Mpofu, G. Holtman, A. Ranjan, et al., Valorization of primary winery wastewater sludge: a scoping study, in: Technical Report TT895/22 Water Research Commission of South Africa Project C2020/2021-00393, 2023.

[51] M. Vital-Jacome, M. Cazares-Granillo, J. Carrillo-Reyes, G. Buitron, Characterization and anaerobic digestion of highly concentrated Mexican wine by-products and effluents, Water Sci. Technol. 81 (1) (2020) 190–198, available from, https://doi.org/10.2166/wst.2020.102. available from.

[52] A. Conradie, G.O. Gigge, T.E. Cloete, Influence of winemaking practices on the chemical characteristics of winery wastewater and the water usages of wineries, S. Afr. J. Enol. Vitic. 35 (1) (2014) 10–19.
[53] M.C. Buelow, K. Steenwerth, L.C.R. Silva, S.J. Parikh, Characterization of winery wastewater for reuse in California, Am. J. Enol. Vitic. 66 (3) (2015) 302–310, available from, https://doi.org/10.5344/ajev.2015.14110. available from.
[54] A. Conradie, G.O. Sigge, T.E. Cloete, Influence of winemaking practices on the characteristics of winery wastewater and water usage of wineries, S. Afr. J. Enol. Vitic. 35 (1) (2014) 10–19.
[56] C.B. Agustini, M. da Costa, M. Gutterres, Tannery wastewater as nutrient supply in production of biogas from solid tannery wastes mixed through anaerobic co-digestion, Process. Saf. Environ. Prot. 135 (2020) 38–45, available from, https://doi.org/10.1016/j.psep.2019.11.037. available from.