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Journal
California Agriculture, 65(2)

ISSN
0008-0845

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Publication Date
2011

Plants in constructed wetlands help to treat agricultural processing wastewater

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Over the past three decades, wineries in the western United States and sugarcane processing for ethanol in Central and South America have experienced problems related to the treatment and disposal of process wastewater. Both winery and sugarcane (molasses) wastewaters are characterized by large organic loadings that change seasonally and are detrimental to aquatic life. We examined the role of plants for treating these wastewaters in constructed wetlands. In the greenhouse, subsurface-flow flumes with volcanic rock substrates and plants steadily removed approximately 80% of organic-loading oxygen demand from sugarcane process wastewater after about 3 weeks of plant growth; unplanted flumes removed about 30% less. In field studies at two operational wineries, we evaluated the performance of similar-sized, paired, subsurface constructed wetlands with and without plants; while both removed most of the oxygen demand, removal rates in the planted system were slightly greater and significantly different from those of the unplanted system under field conditions.

Agricultural processing wastewaters may have high concentrations of organic matter that contaminate surface waters when discharged downstream. At Imagery Estate Winery in Glen Ellen, constructed wetlands with plants were tested for their ability to remove pollutants.

The processing of sugarcane to create molasses for ethanol fuel and feedstock is rapidly expanding across Central and South America, while the number of vineyards and wineries continues to increase across the western United States. Both industries generate process wastewater (PWW) of variable quality, which can have deleterious impacts on receiving surface waters when discharged downstream.

Shepherd et al. (2001) described the negative impacts of winery wastewater downstream, which led to requirements for its control and on-site treatment. Similarly, downstream degradation from sugarcane process waters has been documented in the Ipojuca River of northeast Brazil (Gunkel et al. 2006) and in coastal lagoons of northwest Mexico (González-Farias et al. 2006). Wastewater from molasses processing follows a seasonal variation similar to that of wineries, with high flows and loadings from November through May, followed by harvesting and grape crush in late summer and early fall.

Both winery and molasses process wastewaters are responsive to natural treatment strategies prior to discharge. Remnant wetland systems, relatively common in the drainage channels of Central and South America, may be employed. Likewise, constructed wetlands have been designed and installed to treat winery process wastewater in California. Surprisingly, the role of plants and their associated biofilms in such systems is poorly understood and not well documented relative to treatment performance.

Sugarcane and winery wastewater

Sugarcane, food-processing, winery and other distilleries generate wastewaters from processing and equipment wash-down. These differ greatly from domestic wastewater because of their high organic-matter concentrations, variable flow rates, relatively low levels of nutrients, low pH and lack of pathogens. Gunkel et al. (2006) monitored sugarcane fertigation and wash-down waters (used to clean equipment) in Brazil and noted their very low pH (3.8) and high sodium (1,320 milligrams per liter), salinity and organic loads. Kumar et al. (2007) obtained similar results in India and also noted high sulfates.

To determine the characteristics of sugarcane process wastewater in Mexico, in March 2007 we compared wastewater from a typical processor, Ingenio La Gloria, located on the coast south of Veracruz (Olguín et al. 2008), to sugarcane process wastewater in India and Brazil, and process wastewater from a California winery (table 1). In Mexico, sugarcane process wastewater is typically diluted 10 to 100 times with canal water prior to reuse for irrigation or release into drainage channels, making it similar in quality to that reported for Brazil. The biological oxygen demand (BOD_5, 5-day holding time) and chemical oxygen demand (COD) concentrations (both measures of organic loading), and BOD_5-to-COD ratio, for Brazilian sugarcane wastewater — as diluted for fertigation — were nearly the same as that for the California winery process wastewater. While at much higher concentrations, the BOD_5-to-COD ratio for the Indian sugarcane process wastewater was similar.

Shepherd et al. (2001) proposed that constructed wetlands are an attractive treatment system for moderate-sized wineries, with their ability to assimilate variable and large organic loadings as well as their low maintenance and operational costs. Likewise, process wastewaters can be treated naturally in drainage channels constructed at the outflow of sugarcane processing factories. Such constructed wetlands make use of wetland plants and associated microorganisms on the roots (called biofilms) to degrade organic pollutants such as carbohydrates, proteins and other carbon-based suspended matter that comprise the wastewater's BOD_5 and COD load.

Free-water surface ponds are one type of constructed wetland. In this system, vegetation is planted in base soils below water as deep as 4 feet. These systems are easy to maintain and are acceptable for relatively modest organic loadings, but generally they are not appropriate for winery or sugarcane processing unless the wastewater is pretreated (such as in aerated ponds, for odor and mosquito control).

Another type of constructed wetland, called subsurface-flow or vegetated submerged beds (fig. 1), involves planting wetland vegetation directly into a gravel substrate 3 to 4 feet deep. The wastewater passes through the gravel but does not cover its surface. This system has greater treatment capability but also higher initial installation costs.

Rates of flow into such constructed wetlands are managed so that there is sufficient hydraulic residence time (HRT) for adequate treatment. COD or BOD_5 removal rates are typically modeled as first-order degradation (decay) processes (Shepherd et al. 2001).

TABLE 1. Comparison of process wastewaters (PWW) from sugarcane in Mexico (Ingenio La Gloria, Veracruz), Brazil and India; and a California winery

	Winery	Sugarcane (molasses)				
Parameter*	Calif. PWW*	Brazil fertigation†	Brazil wash-down†	India PWW‡	Mexico PWW	(± SD)
	mg/L					
Chemical oxygen demand (COD)	22,290	23,727	1,050	105,000	118,270	305
Biological oxygen demand (BOD_5)	14,490	10,800	388	52,500	52,200	200
Total Kjendahl nitrogen (TKN)					1,598	106
Nitrogen as ammonia ($N\text{-}NH_3$)					772	16
Nitrogen as nitrate ($N\text{-}NO_3$)	163				312	10
Phosphorus as phosphate ($P\text{-}PO_4$)		67.7 (total)	2.2 (total)		1,100	45
Sulfur as sulfate ($S\text{-}SO_4$)	61			6,250	8,220	197
Potassium (K)					19,250	250
Total solids (TS)	1,120 (TSS)			85,000	106,465	1,534

* Source: Shepherd, Grismer et al. 2001.
† Source: Gunkel et al. 2006.
‡ Source: Kumar et al. 2007.

While plants are understood to be important to treating process wastewater in constructed wetlands, little quantitative information is available. Biofilms are defined as spatially and metabolically structured microbial communities (Nikolaev and Plakunov 2007) that interact with plant roots and the soil-water environment, while constantly adapting to changes in both. As such, plant roots provide the structure needed for biofilm bacteria to process wastewater. Biofilm microorganisms consume organic material and ultimately release carbon dioxide and water, or methane and water, depending on the amount of oxygen present. Since the surface area of plant roots is far greater than that of the sand/gravel/rock substrate alone, and because roots have the ability to partially oxygenate their surfaces, they can support thicker and perhaps more robust biofilms. In addition, plants consume some of the process wastewater nutrients, while roots physically filter them. In some cases the aesthetic appearance of the constructed wetland is not a concern, but the processing plant operators may not see the benefit of maintaining vegetation in planted wetlands. Our investigation was directed at determining the relative value of planted versus unplanted systems.

Constructed-wetland performance

The success of constructed wetlands in treating process wastewaters containing high-strength organic matter depends on several factors related primarily to organic loading, HRTs, the tolerance of selected plants to possibly toxic components in the process wastewater, and plant biofilm activity. Comprehensive research reviews of brewery, winery and related distillery treatment methods for process wastewater have underscored the need for additional research, particularly of full-scale systems and individual processes (Grismer and Shepherd 1998; Grismer et al. 1999, 2000, 2002, 2003). Shepherd, Grismer et al. (2001) evaluated the performance of a subsurface-flow wetland (20 feet long, 8 feet wide and 4 feet deep) in treating winery process wastewater flows ranging from 80 to 170 cubic meters per day at organic loads of 600 to 45,000 milligrams COD per liter (mg COD/l), and measured average removal rates of 98% for COD and 97% for total suspended solids (TSS) when combining the constructed wetland with an upflow sand prefilter. The system also effectively neutralized the pH of the acidic winery wastewater and removed the limited nitrogen (78.2%), sulfide (98.5%), orthophosphate (63.3%), volatile fatty acids (99.9%), tannins and lignins (77.9%) and all settleable solids.

Olguín et al. (2008) achieved similar results from greenhouse-based, fiberglass, subsurface "flumes" (long, narrow boxes 10 feet long, 1 foot wide and 1.6 feet deep), used to treat diluted molasses process wastewater with 2.5- or 5-day HRTs and an average inlet concentration of 1,184 mg COD/l (534 mg BOD_5/l). After 30 to 40 days of plant (*Pistia sagittata*) establishment, the planted flumes achieved average removal rates of 80.2% for COD, 87.3% for BOD_5, 76.1% for total Kjeldahl nitrogen (TKN, the sum of organic nitrogen, ammonia and ammonium) and 68.6% for sulfate during the next month. In the same period, the corresponding control nonplanted flume achieved removal rates significantly lower than that of the planted flume — 40.1% for COD, 60.9% for BOD_5, 55.5% for TKN and 57.0% for sulfate.

Evaluating constructed wetlands in the field requires not only analysis of constituent degradation, or transformation, but also a hydraulic assessment of its bed-flow properties under the variable operating conditions of actual use (Grismer 2005). In the only published field-scale evaluation, Grismer et al. (2003) — using tracer methods developed by Grismer et al. (2001) — measured constructed-wetland degradation constants, HRTs and treatment performance at two operating wineries. System performance was evaluated through daily sampling of total dissolved solids (TDS), pH, total suspended solids, COD, tannins, nitrate, ammonium, TKN, phosphate, sulfate and sulfide.

The larger winery system showed similar COD and tannin removal rates to those of bench-scale columns (constructed of PVC pipes 6 inches in diameter by 24 inches tall), ranging from 49% to 79% (columns) and 46% to 78% (constructed wetlands). Greater removal occurred during the spring, noncrush period. During the crush season, with HRTs of about an hour compared to about 5 days during the noncrush season, the constructed wetland reduced inlet COD by half and other constituents 20% to 30%. Though it had smaller loading rates and greater HRTs, the small winery's constructed-wetland system achieved nearly complete COD removal (from about 8,000 to 5 mg/l) through the use of a recirculation system. These results suggested that the wetland system was quite capable of fully treating winery process wastewater when properly loaded and operated. Understanding the HRTs through tracer study analyses was crucial to the interpretation of water-quality measurements from the wetland.

While there is some literature on bench and pilot-scale testing for loadings and HRTs, scant information is available related to plant and biofilm factors, especially at the field scale. Constructed-wetland systems had not been compared side-by-side, with and without plants, for the high-strength process wastewaters typical of wineries and sugarcane processing. Moreover, the selection of suitable plants for treating process wastewaters depends in part on plants found locally, but little detailed information has been available to help guide that selection.

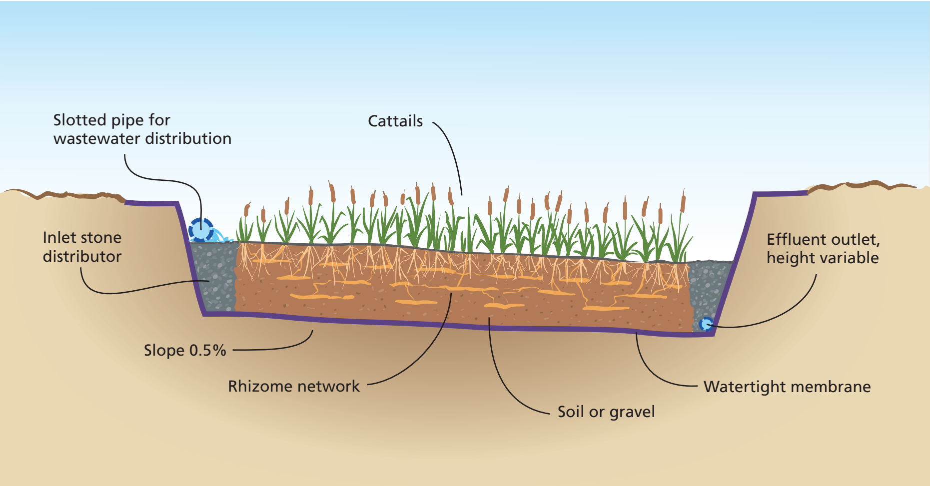

Fig. 1. Cross-section of subsurface-flow constructed wetland.

We conducted complementary green house (Mexico) and field (California) studies for treating molasses and winery process wastewater in constructed wetlands, with and without plants. In the greenhouse studies, we also considered the rate of plant growth and its effect on process wastewater (Olguín et al. 2008). In California, where plants are normally allowed to establish for about a year prior to the introduction of process wastewater, we monitored two planted and unplanted pairs of constructed wetlands at wineries on the Central Coast. In both cases, the wineries anticipated future expansion and chose to build two subsurface systems, one for current operations and another for the expansion. Since the second constructed wetland would not be in use for several years, it was installed without plants, allowing us to monitor and evaluate treatment performance under operating conditions.

Greenhouse and field studies

Mexico greenhouse studies. At the Instituto de Ecología near Xalapa, Mexico, we employed the greenhouse facilities, constructed-wetland flumes and methods, all as described by Olguín et al. (2008). Duplicate flumes were used for each of the three different treatment systems and HRTs. These systems included a surface treatment with aquatic plants, a subsurface-flow treatment with plants, and a subsurface-flow treatment without plants (control). Two HRTs (2.5 and 5 days) were used for the planted systems, while only the 2.5-day time was used in the control. There were 10 flumes in total.

Different HRTs were used to develop preliminary estimates of the degradation constants necessary for field designs of constructed wetlands. Substrate in the subsurface flumes consisted of volcanic rock approximately 1.5 inches (40 millimeters) across, with a net porosity of about 50%, resulting in a flume volume of approximately 45 gallons (170 liters). In the surface treatment, we used

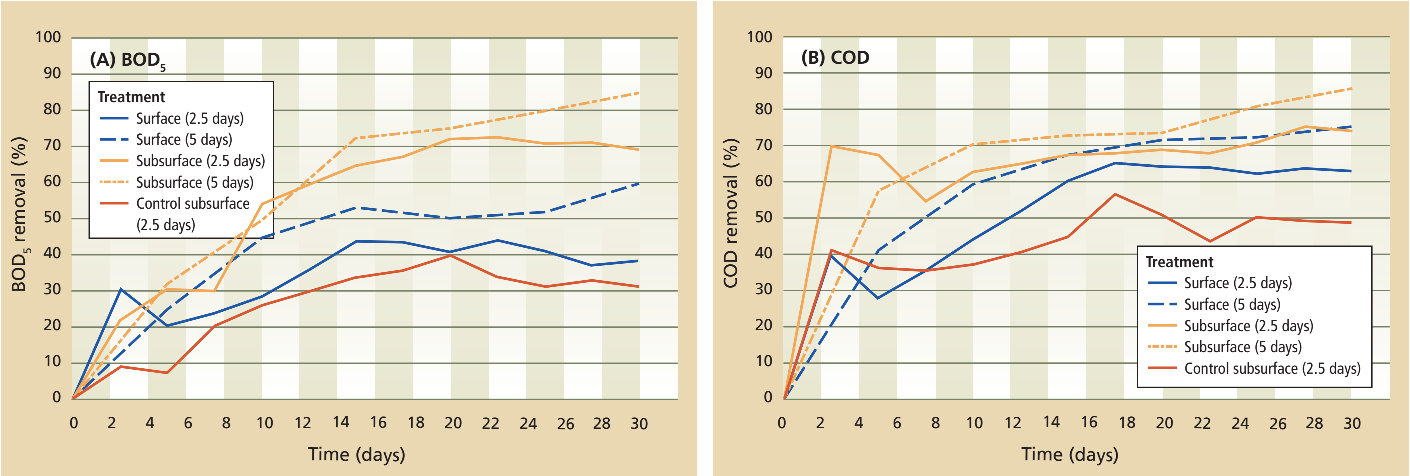

Fig. 2. Daily variation of removal efficiencies for (A) biological oxygen demand, 5 days (BOD$_5$) and (B) chemical oxygen demand (COD) in constructed-wetland greenhouse flume experiments.

the aquatic plant water lettuce (*Pistia stratiotes*), while the subsurface treatment was planted with pickerelweed (*Pontederia cordata*). Plants were allowed 3 weeks to establish and acclimate in local canal water before the experiments were initiated with 100-to-1 diluted sugarcane process wastewater.

Flow rates were carefully maintained, with steady flow provided by Masterflex peristaltic pumps for 30 days of monitoring at the inlet and outlet of each flume. In this study we focused on BOD$_5$/COD removal, based on sampling at 2.5- and 5-day intervals corresponding to flume HRTs. Relatively constant ambient conditions were maintained during May 2006. The overall mean temperature was 79.7°F (26.5°C), while the average evapotranspiration rate was 0.26 inches (6.7 millimeters) per day.

California field studies. Field studies were conducted on the California Central Coast at two wineries (A and B) to evaluate treatment effects on similarly sized, paired (planted/unplanted), subsurface constructed wetlands. At winery A, the systems were sized to handle process wastewater from the production of 14,000 cases of wine, with each wetland designed to treat half this process wastewater (that from about 7,000 cases of production). Each paired wetland was 52 feet by 12 feet by 3 feet deep, with washed pea gravel roughly 0.3 inches (< 8 millimeters) in diameter.

Subsurface wetlands at winery B were also sized to treat process wastewater from 14,000 cases of wine, but the expansion phases were different. One of the wetlands was designed to treat the process wastewater from 8,000 cases and the other from 6,000 cases; they were 55 feet by 14 feet, and 44 feet by 12 feet, respectively, both with approximately 3-foot-deep washed pea gravel.

At both sites, one of the wetlands had been planted with cattails (*Typha dominigensis*), bulrushes (*Scirpus acutus*) and some arrowheads (*Sagittaria latifolia*) the June previous to monitoring. These wetland plants were established though not fully grown by October. In both wineries, the process wastewater was pretreated in septic tanks designed to have a 2-day retention time. Also, both treatments were designed to have 10-day HRTs, though as noted above, in previous field studies the actual field times differed. Winery process wastewater flows were evenly split into the planted and unplanted treatments at the two wineries.

For 2 weeks during the October 2006 harvest, daily water samples were taken from the inlets and outlets of each constructed wetland (planted and unplanted at each winery) with care taken to sample at roughly the same time each day, when wastewater was flowing. Samples for COD, BOD$_5$ and total suspended solids were refrigerated and analyzed daily in the lab, while pH and total dissolved solids were measured directly in the field. As in Mexico, samples were generally analyzed immediately after collection following standard methods using Hach tests accepted by the U.S. Environmental Protection Agency. COD was measured using the closed-reflux colorimetric method adapted from Standard Methods 5220 D. The lower detection limit of the COD analysis was 1 mg COD/l. Total suspended solids were measured using the Hach 2010 Spectrophotometer turbidimetric method. In the field, pH was measured immediately after sampling using the Hach EC10 portable pH meter calibrated against pH 4 and pH 7 standards. Total dissolved solids were measured using the Hach Conductivity/TDS meter. Measured daily plug-flow rates were used to determine the actual HRTs of process wastewater in each constructed wetland following methods described by Grismer et al. (2001, 2003).

Statistical analysis. Because these studies only involved comparisons of mean outlet concentrations from the different treatments, we used simple single-tailed confidence level tests to determine the relative significance of differences in concentrations after they stabilized, or after 15 days in the greenhouse flumes.

Greenhouse flume measurements

System performance. BOD$_5$ (fig. 2A) and COD (fig. 2B) removal rates steadily improved during the first 15 days of the greenhouse tests, after which they stabilized, presumably in response to additional plant growth and acclimation to the process wastewater (table 2). Average BOD$_5$-removal rates after 15 days were 34% for the unplanted control, 41% and 53% for the surface system, followed by 70% and 78% for the subsurface system, with HRTs of 2.5 and 5 days in both treatments, respectively. All mean outlet BOD_5 concentrations differed at greater than 99.9% confidence levels ($P < 0.00005$).

Similarly, mean COD-removal rates after 15 days of sampling were 49% for the control, 63% and 71% for the surface system, followed by 70% and 78% for the subsurface system, again at HRTs of 2.5 and 5 days, respectively. With the exception of the means comparison between outlet COD concentrations from the subsurface (2.5 days) and the surface (5 days) treatments having a significant difference at the approximately 96% confidence level, all remaining mean outlet COD concentrations differed at greater than 99.9% confidence levels ($P < 0.00005$).

The greenhouse studies showed that (1) the subsurface treatment outperformed the surface treatment in terms of BOD_5 and COD removal at both HRTs; (2) not surprisingly, greater HRTs resulted in greater removal rates of BOD_5 and COD for both systems; and (3) the planted subsurface system significantly outperformed the unplanted control in terms of BOD_5 and COD removal.

BOD_5 and COD degradation. The use of two different HRTs in the greenhouse studies enabled preliminary assessment of the simple first-order degradation constants (K) for each system, and how they varied with time during the 30-day test period. Such information is useful for the field designs of constructed-wetland systems. In addition, because COD is a measure of all possible oxygen-consuming material in the process wastewater, changes in BOD_5-to-COD ratio during the experimental period provide an indication of the relative ability of each system to degrade progressively more-recalcitrant organic compounds in the process wastewater (fig. 3). The K values for COD increased and appeared to stabilize after about 2 weeks. In this study, we found stable degradation constants of 0.2 and 0.4 per day for the surface and subsurface systems, respectively; this is much lower than the constant of about 1.5 per day found by Shepherd, Tchobanoglous et al. (2001) in pilot-scale, subsurface treatment of winery process wastewater in Davis used as the basis for our field experiment design. Our smaller K values may be due to the larger volcanic rock substrate used in the flumes as compared to the pea gravel used by Shepherd, Tchobanoglous et al. (2001).

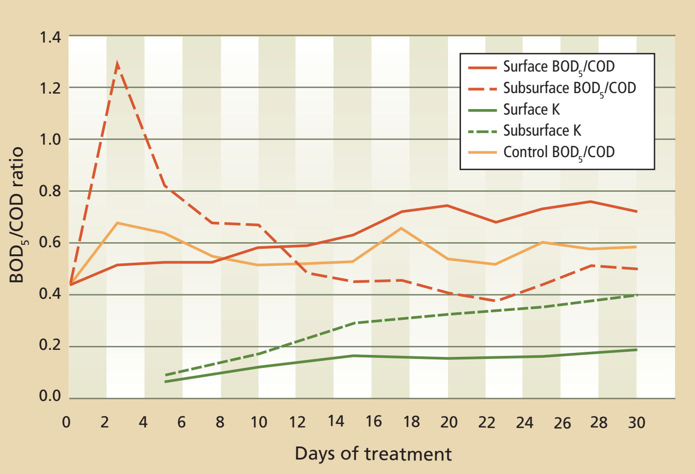

Fig. 3. Variation of constructed-wetland treated wastewater BOD_5-to-COD ratio and first-order degradation constants (K(1/d) during experimental period.

Perhaps more interesting is the change in average BOD_5-to-COD ratios from those of the initial wastewater stream (BOD_5-to-COD = 0.44). In the subsurface treatment, the ratio dramatically increased to greater than 1.0, leveling off to about 0.5 after 2 weeks. Meanwhile, this ratio remained approximately unchanged in the control at 0.55 to 0.60, and steadily increased to roughly 0.75 in the surface treatment. The latter ratio reflects the greater treatment capability of the combined plant/gravel biofilm system after acclimation in the subsurface system compared to that of the surface system.

TABLE 2. Mean outlet chemical (COD) and biological (BOD_5) oxygen demand concentrations from greenhouse flumes after 15 days of flow through constructed wetlands

	BOD_5			COD		
Treatment (HRT*)	Inlet	Outlet	Outlet SD†	Inlet	Outlet	Outlet SD
	······· *mg/L (n)* ·······			······· *mg/L (n)* ·······		
Control (subsurface)	522 (14)	344	16.7	1,183 (28)	605	49.5
Surface (2.5 hours)	522 (14)	307	14.1	1,183 (28)	437	21.0
Surface (5 hours)	522 (8)	242	23.0	1,183 (16)	338	34.5
Subsurface (2.5 hours)	522 (14)	159	16.2	1,183 (28)	359	42.9
Subsurface (5 hours)	522 (8)	116	27.3	1,183 (16)	260	60.4

* Hydraulic residence time.

† Standard deviation.

In the subsurface system, 3 to 4 weeks were sufficient for plant establishment to achieve the steady removal rates reported by Olguín et al. (2008). Overall, COD removal rates indicate that the use of constructed-wetland systems in the drainage canals leaving sugarcane processing facilities should be advantageous for improving downstream water quality.

Winery subsurface-flow systems

Winery A. Under actual field operations, the performance of constructed-wetland systems in California was variable depending on the winery process wastewater flows and loading rates. Due to greater wine production than anticipated at winery A, inlet loading (flow and COD concentrations) was much greater and more variable than anticipated, resulting in daily HRTs of roughly half the design value of 10 days, although constant. After 5 days of sampling at winery A, inlet COD loading peaked from roughly 60,000 mg/l to more than 130,000 mg/l for about 2 days due to uncollected juice flowing into the treatment system. This situation was corrected, and inlet COD concentrations steadily decreased to about 60,000 mg/l by day 11 of sampling. Outlet COD concentrations ranged from approximately 600 to 5,200 mg/l from the planted treatment to 600 to 8,800 mg/l from the unplanted treatment at winery A. Inlet total-suspended-solids

Piping disperses process wastewater across the width of a constructed wetland at a Paso Robles winery. Samples were taken at the outflow (not shown) and the far end of the wetland, which was designed to handle wastewater generated by producing 14,000 cases of wine.

concentrations ranged from 160 to 450 mg/l, and corresponding outlet concentrations ranged from 20 to 160 mg/l and 50 to 260 mg/l from the planted and unplanted wetlands, respectively.

Winery B. Conversely, at winery B full wine production was not achieved, and daily flow rates and loadings were much smaller and less variable. As a result, there were different flow rates to each constructed wetland and much greater HRTs, about double the design value of 10 days. Flow and loading conditions at winery B were more typical; inlet COD values were as high as 7,000 mg/l and outlet values ranged from 14 to 48 mg/l and 68 to 138 mg/l for the planted and unplanted treatments, respectively. Average total-suspended-solids concentrations at the winery B inlet were similar to those at winery A, ranging from 240 to 420 mg/l, but corresponding concentrations at the outlet were far less, ranging from 18 to 34 mg/l and 26 to 64 mg/l for the planted and unplanted wetlands, respectively. The average removal rates for total suspended solids of 76% (53% for unplanted) as compared to 91% (85% for unplanted) reflect the much shorter HRTs encountered at winery A compared to winery B.

Plants and treatment performance. Because COD and total-suspended-solids concentrations at the inlet of winery A were roughly 10 times greater than those at winery B — and as a result, HRTs were only one-third that for winery B — concentrations at the outlet were also considerably greater at winery A (table 3). This fortuitous change enabled us to better evaluate the effects of plants on treatment performance across a greater range of loading conditions than originally planned.

The mean outlet concentrations of COD, total suspended solids, total dissolved solids and pH between the planted and unplanted wetlands at winery A all differed significantly at greater than 99% confidence levels. Similarly, at winery B, despite significantly greater HRTs in the unplanted treatment, mean outlet concentrations between the planted and unplanted treatments were also significantly different at greater than 99% confidence levels. Outlet concentrations differed at the 95% confidence level.

At both wineries, salinity and total-dissolved-solids concentrations increased as a result of evapoconcentration within the constructed wetland. The subsurface treatments at both wineries were successful in substantially reducing COD and total suspended solids at the outlet by more than 96% and 76%, respectively, with the planted system significantly outperforming the unplanted system. Finally, acidic pH of the process wastewater at both winery inlets was more successfully neutralized by the planted than the unplanted wetlands.

Overall, the field evaluation demonstrated that plants can play a significant role in treating process wastewater from wineries. While the planted

TABLE 3. Field inlet/outlet monitoring (14 days) of subsurface-flow constructed wetlands for process wastewater treatment at two California wineries

	HRT*		COD			TSS			TDS			pH		
Parameter	Planted outlet	Unplanted outlet	Inlet	Planted outlet	Unplanted outlet	Inlet	Planted outlet	Unplanted outlet	Inlet	Planted outlet	Unplanted outlet	Inlet	Planted outlet	Unplanted outlet
	days		*mg/L*											
Winery A														
Mean	6.0	6.0	72,965	2,321	4,770	297.9	71.3	140.5	639	1,447	1,910	4.50	6.41	5.81
Standard deviation	1.6	1.6	29,066	1,512	2,649	95.0	44.6	59.2	33	366	321	0.28	0.33	0.33
P value/CL†				0.0013	> 99%		0.0002	> 99%		0.0002	> 99%		< 0.0001	> 99%
Average removal (%)				96.8	93.5		76.1	52.8						
Winery B														
Mean	17.5	24.1	5,080	30.8	106.0	324	27.5	44.50	615	1,178	1,401	5.35	6.96	6.52
Standard deviation	4.6	6.3	1,211	9.2	23.3	54.6	6.10	10.02	28.7	168	244	0.56	0.17	0.17
P value/CL	0.0008	> 99%		0.0465	> 95%		< 0.0001	> 99%		< 0.0024	> 99%		< 0.0001	> 99%
Average removal (%)				99.3	97.9		91.1	85.5						

* HRT = hydraulic residence time; COD = chemical oxygen demand; TSS = total suspended solids; TDS = total dissolved solids.

† CL = confidence level.

constructed wetlands were less than 1 year old and not fully developed, they showed consistently better removal of COD and total suspended solids, as well as better pH neutralization.

Natural treatment systems are effective in reducing organic-matter levels in wastewater, and even more so when they incorporate plants. At Lemon Winery in Sebastopol, constructed wetlands include a planted bed (center) and an unplanted pond (middle right).

Understanding natural treatments

Natural wastewater treatment systems have been effective in treating process wastewaters from fruit, wine and sugarcane processing, but many of the associated mechanisms are poorly understood, particularly at the operational scale.

In our greenhouse studies, planted subsurface flumes with volcanic rock substrates removed approximately 80% of the inlet BOD_5 and COD loading from molasses process wastewater, approximately 1,200 mg COD/l after about 3 weeks of plant growth. This ultimate removal rate was similar to the steady rate achieved in these same flumes later. The planted flumes outperformed the unplanted flumes by roughly 30% in terms of COD removal. The steady increase in BOD_5-to-COD ratio in the effluent of planted versus unplanted flumes suggests that the plant-biofilm system was better able to degrade more-recalcitrant compounds in process wastewater.

Plants can play a significant role in treating process wastewater from wineries.

In the winery studies, operational conditions resulted in overloading and underloading of the constructed wetlands even though HRTs were designed to be the same. Average organic loadings spanned roughly 5,000 to 75,000 mg COD/l at HRTs of roughly 20 to 6 days, respectively. While total-suspended-solids concentrations at the inlets were similar at both wineries, much greater HRTs at one winery resulted in greater COD removal rates. At both wineries, the planted wetlands outperformed unplanted wetlands, with COD removal of 98% versus 95%, respectively; total-suspended-solids removal of 84% versus 69%, respectively; and better pH stabilization and less total-dissolved-solids in the planted wetlands.

The slightly greater COD removal rates at the wineries may be associated with the finer substrate material used (pea gravel versus volcanic rock), plus the pea gravel possibly had greater cation exchange, or adsorption capacities, or simply a greater surface area for biofilm development. Our laboratory is investigating this issue. Nonetheless, we expect the performance of the field constructed wetlands to improve as the plant-biofilm system is further developed. Overall, as in the greenhouse studies, the field studies underscored the importance of plants to the treatment performance of constructed wetlands for the variable, high-strength process wastewaters typical of fruit, wine, distillery and sugarcane processing.

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