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Short Communication

Low-energy treatment of colourant wastes using sponge biofilters for the personal care product industry

S.Z. Ahammad [a], A. Zealand [a], J. Dolfing [a], C. Mota [a], D.V. Armstrong [b], D.W. Graham [a,*]

[a] School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK
[b] H20 Group, Birtley, County Durham DH3 2PW, UK

HIGHLIGHTS

- ▶ Treating hair colourant wastes in the PCP industry is very energy intensive.
- ▶ New biofilter designs were tested for treating high strength colourant wastes.
- ▶ Packed- and sponge-media designs removed by COD and TN > 90% and 60%, respectively.
- ▶ Aerated sponge biofilters tolerated high oxidant levels better than other designs.
- ▶ Sponge reactors can reduce energy costs by >40% over current practices.

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ABSTRACT

Four trickling biofilter designs were assessed as low-energy alternatives to aerobic activated sludge (AS) for the treatment of personal care product industry wastes. The designs included partially submerged packed-media and sponge reactors with and without active aeration. Partial submergence was used to reduce active aeration needs. Simulated colourant wastes (up to COD = 12,480 mg/L, TN = 128 mg/L) were treated for 201 days, including wastes with elevated oxidant levels. COD and TN removal efficiencies were always >79% and >30% (even without aeration). However, aerated sponge reactors consistently had the highest removal efficiencies, especially for TN (~60%), and were most tolerant of elevated oxidants. This study shows sponge biofilters have great potential for treating colourant wastes because they achieve high treatment efficiencies and reduce energy use by >40% relative to AS systems.

1. Introduction

Personal care product (PCP) industries manufacture a broad variety of cosmetic and related products, which have a business value of >$250 billion per year (PCPC, 2010). A major portion of the total cosmetic market is comprised of hair colourant products (~8%) that account for $3.2 billion in the European economy (EC, 2010). Four distinct classes of colourants exist (Kirkland et al., 2005), including permanent (oxidative), semi-permanent (non-oxidative), metal salts, and natural dyes, all of which are approved by the European Commission (EC, 2010) and the U.S. Food and Drug Administration (USFDA, 1997). Further, oxidative dyes account for ~80% of total hair colourant market (Corbett, 1999); therefore, treating wastes from colourant manufacture is both of economic and environmental importance.

Liquid wastes produced in PCP manufacturing are primarily treated by aerobic activated sludge (AS) systems coupled with physico-chemical methods (El-Gohary et al., 2010), although biological methods are generally favoured because they produce more tractable solids residuals (Kurt et al., 2007). Anaerobic biological processes typically are not used because of the presence of oxidants in colourant wastes that inhibit anaerobic microorganisms (Ahammad et al., 2012). Therefore, hair colourant waste treatment uses aerobic processes that require copious active aeration because of high organic loadings (e.g., up to 20,000 mg/L COD), making AS very expensive in terms of energy costs. In fact, up to 10% of the total operating budget of a PCP factory can be for oxygen provision in their aerobic waste treatment units. Therefore, there is an urgent need for alternate biological waste treatment approaches, which both consider the relative toxicity of constituents in the waste and also the cost of energy for aeration.

A new approach is examined here for the treatment of colourant wastes that is designed to reduce energy consumption and sustain treatment performance. Given that aerobic conditions are better for oxidant-containing colourant wastes and active aeration is

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* Corresponding author. Address: School of Civil Engineering and Geosciences, Cassie Building, Newcastle University, Newcastle upon Tyne NE1 7RU, UK. Tel.: +44 0 191 222 7930; fax: +44 0 191 222 6502.
E-mail address: d.graham@ncl.ac.uk (D.W. Graham).

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expensive, reactor designs that permit passive and-or semi-passive aeration have some promise (e.g., trickling filters). However, careful biofilter design is needed to ensure plugging and odours do not occur, and that there is adequate surface area-to-volume capacity for microbial attachment. Recent work in Japan suggests a possible option, which is the use of sponges as packing material in biofilter reactors (Machdar et al., 2000; Tawfik et al., 2006; Tandukar et al., 2007). Sponges can be designed to have almost any surface area-to-volume capacity and can be packed in almost any configuration. However, plugging can be a problem, therefore gravity-fed operation and partial submergence of waste in the sponge media are potentially advantageous (analogous to creating a pseudo-vadose zone in soils). In such a design, the top of the sponge would be passively supplied with oxygen and the bottom of the sponge would be oxygen-free, providing layers for aerobic biodegradation (above) and anaerobic solids digestion (below) within the same reactor.

Four continuous-flow biofilter reactors were compared here to assess the impact of packing material (sponge vs. plastic packed-media) and active aeration on COD and total nitrogen (TN) removal from simulated colourant wastes. Two reactors had sponge cores, whereas two had packed-media of similar volume, and one of each reactor-pair was aerated from below. The reactors were provided progressively stronger colourant wastes and extra oxidants to assess reactor performance. Relative energy costs also were estimated for each design. Although COD and TN removal efficiencies were slightly higher with extra aeration, sponge reactors were superior to packed-media systems in treatment performance.

2. Methods

2.1. Simulated colourant wastewater

The simulated wastewater for this study was constructed by mixing individual ingredients used in the colourant manufacturing process, which include three base components and four different hair dye products, as reported previously (Ahammad et al., 2012). The reactors were initially fed low-strength influent (COD = 1560 mg/L) and the feed strength was increased in four stages over 162 days to an ultimate COD of 12,480 mg/L (see Fig. 1). This progressive increase in waste strength was done to slowly acclimatize the reactors to wastes typical of a PCP factory; allow biofilms to develop in the reactors; and to generally assess how sponge versus packed-media reactors performed under different conditions. Between 163 and 201 days, waste oxidant content was increased (i.e., hydrogen peroxide and some unknown ingredients) by an average of 20% (stage 5). This oxidant level was employed to reflect typical variations seen in PCP factory wastes.

2.2. Reactor inoculum and designs

Return activated sludge from an aerobic sewage treatment plant in Northern England, which had active nitrification, was used as the reactor inoculum. One of tangential goals of the project was to assess whether nitrification could be sustained in the reactors (Araki et al., 1999; Yan and Hu 2009), although this was less important for colourant waste treatment. The aerobic sludge was acclimatized with colourant wastewater in aerated batch reactors for 35 days before transferring the sludge to the respective reactors, which were then operated in continuous mode until the end of the experiment. Sixty-seven percent (v/v) of the working volume was provided with seed sludge in all reactors.

Four laboratory-scale Plexiglas reactors with working volumes of 2 L were used in the study, designated packed-media aerated (PMA), sponge aerated (SA), packed-media non-aerated (PMN), and sponge non-aerated (SN), respectively. The packed-media was comprised of 16 mm diameter polypropylene Pall rings, whereas sponge media was made of polyurethane with 0.63 mm pore size, 0.97 void fraction, 30 kg/m^3 density and 256 m^2/m^3 specific surface area. In both cases, the media was supported by a perforated resting plate perched 10 cm above the bottom the reactor.

All four reactors were gravity fed from above and liquid levels in the reactors were maintained at half- to two-thirds depth relative to the top of media to maintain a passive aeration zone. Air was supplied via a rotameter to the PMA and SA reactors below the resting plate to provide extra oxygen to those units, although feed rates were relatively low: adequate to maintain ~2.0 ppm dissolved oxygen levels in the reactor bottoms. No active aeration was provided to the PMN or SN units as both designs permitted passive aeration in their unsaturated zones. Therefore, depending on oxygen transfer, a gradient of aerobic to micro-aerophilic to anaerobic conditions existed with depth in the units. However, it was not possible to exactly measure oxygen gradients without damaging the integrity of the media, especially in the sponge reactors. All four reactors were operated at a 3-day HRT, but organic loading rates were varied (see Fig. 1). The reactors were maintained at room temperatures (~23 °C) and reactor pHs were consistently between 7.5 and 8.3.

2.3. Chemical analysis

Chemical oxygen demand (COD), total carbon (TC), Total Kjeldahl nitrogen (TKN), ammonia (NH_3–N), nitrite (NO_2–N), nitrate (NO_3–N) and phosphate (PO_4–P) were quantified to characterise the influent conditions and overall performance of the different reactor designs. All samples were filtered (0.2 μm; VWR, UK) prior to analysis, therefore soluble values are reported for all parameters. COD was determined according to standard methods (APHA, 1998) and TC was quantified employing an automated TOC analyzer (Shimadzu, Germany). TKN and NH_3–N levels were estimated using Spectroquant test kits (Merck, Germany) according to manufacturer's instructions. NO_2–N, NO_3–N, and PO_4–P were quantified using ion chromatography (ICS-1000, Dionex, USA), a conductivity detector and anion column (Ionpac AS14A, 4 × 250 mm analytical, Dionex, USA). The eluent was comprised of 8.0 mM Na_2CO_3 and 1.0 mM $NaHCO_3$, and the flow rate was 1.0 ml/min. Total nitrogen (TN) was defined as the sum of TKN, NH_3–N, NO_2–N and NO_3–N.

2.4. Data analysis

Reactor performance was statistically compared between reactors and operating conditions using the two-sample *t*-test in SPSS Version 19 (SPSS Inc., USA). Paired comparisons were made between mean removal efficiencies for COD and TN for each reactor-pair within each stage (stage 1 through 5), reactor-pairs using combined data from stage 1 to 4, and each reactor design before and after oxidant addition (i.e., stages 4 and 5). Data were log-transformed prior to statistical analysis to enhance normality, if needed. Unless otherwise noted, 95% confidence levels ($p < 0.05$) were used to define significance.

2.5. Energy calculations

A key factor in promoting the industrial application of a new treatment technology is the energy cost per kg of treated COD. Therefore, the energy cost of aeration and pumping was calculated and compared with similar costs for aerobic AS systems. Three cases were considered here: aerated packed-media and sponge reactors versus non-aerated packed-media and sponge reactors versus AS systems. Pumping costs were assumed the same for all