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Paclobutrazol removal from irrigation water using a commercial-scale granular activated carbon system

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ABSTRACT

A commercial-scale granular activated carbon (GAC) system was evaluated for removal of the plant growth regulator paclobutrazol [(2RS,3RS)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1H-1,2,4-triazol-1-yl)pentan-3-ol] from recaptured irrigation water in an ornamental greenhouse operation. This greenhouse collected and re-used irrigation drain water from 8.1 ha of subirrigated greenhouse production space, resulting in approximately 5.4 million L of recycled irrigation water filtered annually by GAC. Recaptured water was pre-filtered with polyester bag filters and then passed through three 1000 L (454 kg) GAC vessels in series before being recycled for irrigation purposes. Each GAC filter contained 8 × 30 US mesh (595–2380 μm) bituminous coal-based GAC. In Experiment 1, paclobutrazol concentration was analyzed in pre- and post-GAC filtration samples approximately weekly with a total of 55 samples between March 2015 and August 2016. The highest concentration of paclobutrazol found in recycled irrigation water was 72.5 $\mu g\, L^{-1}$, whereas residual concentration after GAC was below a target 5 $\mu g\, L^{-1}$ in all samples. In Experiment 2, water samples collected pre- and post-GAC filtration four times over a ten-week period during a peak period of plant production and included chemical analysis and a broccoli bioassay. The GAC filtration in Experiment 2 was effective at paclobutrazol removal despite wide variation in flow rates and resulting contact times (11–31 min) through the filter. In Experiment 3, samples were taken in a random order from the outlet of each individual GAC filter with contact times of 0, 10, 21, or 31 min. After 31 min of GAC contact time, broccoli bioassay plants were 7% (0.22 cm) shorter than control plants that received 0 $\mu g\, L^{-1}$ paclobutrazol. There was a 30% average reduction in paclobutrazol concentration with the addition of each GAC filter or approximately 10 additional minutes of contact time with each GAC filter, reduced from 16.3 $\mu g\, L^{-1}$ for the control to 1.7 $\mu g\, L^{-1}$ after 31 min contact time. A partial budget showed GAC media replacement to be the highest operating cost item associated with treating recaptured irrigation water, contributing approximately 30% of the total annual cost of $13,020. There was no indication of reduced effectiveness of GAC paclobutrazol removal after approximately one year of filtration without GAC replacement.

1. Introduction

Production of ornamental crops requires frequent applications of pesticides including insecticides, herbicides, and plant growth regulators to maintain crop quality and uniformity. Paclobutrazol ((±)-(R*,R*)-β-(4-Chlorophenyl)methyl-α-(1,1-dimethylenthyl)-1H-1,2,4-triazole-1-ethanol) is a commonly-used plant growth regulator (PGR) in the ornamental plant industry because of its high level of activity and cost-effectiveness. This PGR can be applied by container drenches, dips of propagation trays, and foliar applications by overhead boom sprayers. Paclobutrazol is used as a growth retardant for reducing internode length of vigorous species. Misapplications can delay flowering, reduce flower size, and cause stunted growth (Boldt, 2008; Runkle, 2012; Whipker, 2017). Million et al. (2002) observed a 30% reduction in begonia height when plants were sub-irrigated with 5 $\mu g\, L^{-1}$ paclobutrazol in the nutrient solution. Pansies, vinca, chrysanthemum, impatiens, and petunia have also shown high sensitivity to paclobutrazol in the ppb range (Million et al., 1999; Whipker, 2017). Given that paclobutrazol has a half-life of approximately 6 months in water, paclobutrazol residues may be present in recaptured irrigation

Abbreviations: ANOVA, Analysis of variance; EBCT, Empty bed contact time; GAC, Granular Activated Carbon; GC–MS, Gas chromatography-mass spectrometry; NTU, Nephelometric turbidity unit (NTU); PGR, Plant growth regulator

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water for several growing seasons if not treated (Massachusetts Department of Environmental Protection (MDEP, 2012). Residues of paclobutrazol concentration as high as 50 μg L^{-1} have been found in catchment ponds in ornamental greenhouse operations that apply PGRs frequently and recapture irrigation water (Fisher et al., 2016). Grower operations have anecdotally reported significant losses in crop quality caused by paclobutrazol residues accumulating in their recaptured irrigation water. This has prompted several ornamental greenhouse operations to invest in granular activated carbon (GAC) filtration to remove paclobutrazol.

Activated carbon is categorized as a multiple-purpose removal agent, with the ability to remove various chemicals such as organic compounds, suspended solids, and pesticides simultaneously (Moeller, 2011). Several other methods have been used to effectively remediate agrichemical contaminants from irrigation water such as ozonation, UV radiation, nanofiltration, and phytoremediation (Bruggen et al., 1998; Al Hattab and Ghaly, 2012; Majsztrik et al., 2017). Activated carbon has advantages of simplicity and relatively low capital cost compared with other remediation options (Environmental Protection Agency (EPA, 2001; USACE, 2001; Burkul et al., 2015). GAC is also used for pesticide spills, cleaning spray equipment, application to turf for pre-emergence herbicide inactivation, and treating herbicide residuals in agricultural fields between crop rotations (Fishel, 2008). A small-scale GAC system was highly effective at removing paclobutrazol from tap water under controlled research conditions (Grant et al., 2018). However, because of the recent adoption of GAC by the greenhouse and nursery industry, there is a lack of research on the use of GAC for paclobutrazol removal from recaptured irrigation water in a commercial-scale operation. Our objective was to determine the cost and effectiveness of a commercial-scale GAC system for removing paclobutrazol from recaptured irrigation water in a greenhouse operation.

2. Materials and methods

2.1. Overview of production site and Water filtration systems

Irrigation water from 8.1 ha of production area was recaptured and treated by GAC before re-application to subsequent crops. Three experiments were conducted using the GAC system. In Experiment 1, 55 samples were collected on an approximately weekly basis pre- and post-GAC filtration for analysis of paclobutrazol concentration by a commercial pesticide analysis laboratory (Waters Agricultural Laboratories, GA) using gas chromatography-mass spectrometry (GC–MS). In Experiment 2, additional samples were collected pre- and post-GAC filtration over a ten-week period during a season of peak plant production, and were tested using both GC–MS and a broccoli bioassay. Experiment 3 ran during this ten-week period, samples were collected between the three GAC tanks to determine the effect of increasing amounts of GAC filtration on paclobutrazol concentration (tested via GC–MS and the broccoli bioassay). Broccoli (*Brassica oleracea*) was chosen based on previous studies showing its high sensitivity to paclobutrazol concentration (Million et al., 1999, 2002).

A partial budget for the cost of treating recaptured irrigation water was developed based on information gained from the grower operation and the supplier of the GAC filtration system. Cost categories including capital, consumables, labor, and water testing costs were used to calculate the total yearly cost of treating recaptured irrigation water. Total yearly costs were calculated for the pre-filtration system used to remove suspended solids from water prior to entering the GAC system, the GAC filters, and the booster pump used to pass recaptured irrigation water through both filtration systems. The volume of recaptured irrigation water treated by GAC per year was also estimated based on the flow rate and duration of time that the booster pump was in operation.

The grower operation assessed in this study consisted of 15.8 ha of glass greenhouse production of containerized ornamentals. Irrigation water was recaptured and recycled from 8.1 ha of this production space.

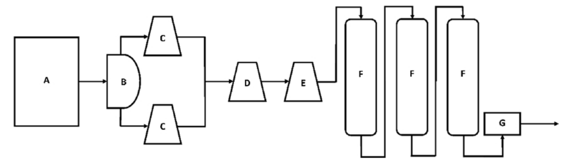

Fig. 1. Commercial-scale GAC system schematic diagram. Diagraph shows pre-filtration and GAC filtration systems consisting of water collection basin (A), booster pump (B), two 50 μm bag filters in parallel (C), 25 μm bag filter (D), 5 μm bag filter (E), three GAC filters in series (F), and sanitizing chemical (peroxyacetic acid) injection (G).

The grower operation suspected losses in crop quality due to the accumulation of paclobutrazol in recaptured irrigation water, and installed a GAC filtration system in April 2014. Plant growth regulator applications including a paclobutrazol product (Piccolo™, Fine Americas Inc., CA), were applied frequently throughout the growing season through overhead boom sprayers. Excess solution not taken up by the plants during each irrigation or pesticide application event was captured through holes in the concrete floors on which plants were grown. Recaptured water was collected in a concrete tank, then pre-filtered, and passed through a GAC system before being re-applied to crops (Fig. 1). The pre-filtration system consisted of polyester bag filters (two 50 μm filters in parallel followed by a 25 and 5 μm in series). Bag filters were replaced at maximum once per day during times periods of peak production. Pre-filtered water passed directly into three 1000 L (454 kg) GAC filters placed in series. Having multiple GAC filters in series allows for the alternation or replacement of individual filters, and increases total GAC contact time as needed (Chowdhury et al., 2013).

In Experiments 2 and 3, the duration of time solution came in contact with GAC was calculated. For GAC filtration of municipal water treatment, empty bed contact time (EBCT) is used as a design parameter (Chowdhury et al., 2013). This value is calculated by dividing the total volume of GAC filter(s) by the flow rate of water passed through the GAC system, not taking into account the proportion of the filter volume taken up by with solid GAC substrate. The porosity of the GAC material (63% by volume for the GAC used in the grower location, estimated by displacement of water in a laboratory procedure) was therefore also calculated to more precisely estimate contact time.

Contact time in seconds (*CT*) was calculated from Eq. (1):

$$CT = ((P * V)/R)*60 \quad (1)$$

Where *P* represented the pore space of GAC (63%), *V* was the volume of the filter canisters in liters, and *R* was the flow rate of chemical solution (L min^{-1}) passing through the filter.

Each GAC filter contained 8 × 30 US mesh (238–595 μm) bituminous coal-based GAC (Carbon Filtration Systems Inc., RI). For organic contaminant removal, bituminous coal GAC has advantages of availability, performance capabilities, and a relatively low cost compared with other GAC products (Chowdhury et al., 2013). The grower operation backwashed their GAC filters a minimum of twice per year and the GAC particles were replaced annually by the company sourcing the GAC media. Water exiting the GAC system was treated with a sanitizing agent (SaniDate, BioSafe Systems) for pathogen removal, and was then stored in four holding tanks. When water was needed for irrigation purposes, stored water flowed from the holding tanks through a fertilizer injector which supplemented macronutrients to a target concentration of 100 mg L^{-1} nitrogen. Because GAC has the ability to adsorb iron chelate during filtration (Yang et al., 2012), 1 mg L^{-1} of chelated iron was also injected into the irrigation water before reuse. When the volume of stored recycled water failed to meet irrigation demand, supplemental well-water was pumped into the irrigation system as needed.