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Coal Bottom Ash and Pine Wood Peelings as Root Substrates in a Circulating Nutriculture System

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Abstract. **'Inca Yellow' marigolds *(Tagetes erects* L.) were planted in polyethylene bags containing coal bottom ash (CBA), pine wood peelings (PWP), a mixture of 1 CBA: 1 PWP (v/v), and loose Grodan rockwool (RW) and grown in a circulating nutriculture system. Three fertigation frequencies of 12,6, or 4 cycles per 12-hour light period were set with a duration of 5 minutes each. Flower diameters of marigolds grown in CBA, PWP, and CBA-PWP exceeded flower diameters of RW-grown marigolds, and days from planting to harvest were less in CBA and CBA-PWP than in the other two media. There was no interaction between medium and fertigation frequency. Foliar analysis showed no significant differences in plant elemental composition among root media or fertigation frequencies. Postharvest PWP water extracts contained higher P levels than extracts of other media, and CBA-PWP water extracts contained higher K, Ca, and Mg. In the CBA-PWP mixture, decomposition products from PWP may have increased P volubility and solubilized the K, Ca,-and Mg-in CBA.**

Nutriculture involves culturing plants in an inert substrate, such as gravel or rockwool (RW), or in air (aeroponics) (Nelson, 1991). Using nutriculture systems controls crop nutrient and moisture levels; this control is not possible with conventional soilless media culture. Circulating nutrient solutions reduces environmental concerns over groundwatercontamination from greenhouse chemical runoff and promotes water conservation (Biernbaum et al., 1988; Sallee, 1988).

One justification for using RW in nutriculture systems has been the belief that it is an inert substance (Nelson, 1991). However, a recent study indicated that Grodan loose RW released measurable amounts of diethylene-triamine-pentaacetic acid-extractable Fe, Cu, and Mn (Rupp and Dudley, 1989).

Coal bottom ash (CBA) and pine wood peelings (PWP) are industrial waste products that currently are used in limited quantities (American Coal Ash Association, 1988). These products often are disposed of in solid-waste landfills but can be purchased at a lower cost than comparable volumes of RW.

The combination of CBA and PWP with peat and vermiculite as a root medium increased dry weight and flower count of 'Nellie White' Easter lilies *(Lilium longiflorum* Thunb.) (Bearce and Leach, 1987) but reduced dry weight, height, and bract size of 'Brilliant Diamond' poinsettias *(Euphorbia pulcherrima* Wind ex Klotzsch) (Bearce and Leach, 1989).

Neal and Wagner (1983) documented the use of CBA as a container medium and reported no large physical or chemical disadvantages; some micronutrients and heavy metals were released. The top dry weight and top visual rating of 'Hinodegiri' azaleas (Rhodo*dendron obtusum* Lindl.) grown in CBA and pine bark mixes outdoors decreased as CBA increased in the mixes; plants grown in aged CBA grew larger than those grown in fresh CBA. In a greenhouse study, top dry weight was equal to or greater than that of the control in all mixes and ages, while top visual rating decreased at >50% CBA (Wagner and Neal, 1984).

The objectives of this investigation were to 1) compare marigold growth performance in CBA and PWP with that in RW in a circulating nutriculture system, 2) determine an optimal fertigation frequency, and 3) determine some differences in chemical reactivity of the media to a nutrient solution. Physical characteristics of the media also were compared.

A circulating nutriculture bench was constructed on a 0.76-m-high × 1.37-m-wide × 7.32-m-long concrete soil bench in a glasshouse. The plywood benchtop was covered with O. 10-mm-thick white polyethylene plastic and sloped 8% to drain the nutrient solution to vinyl rain gutters located beneath the outer edge of the benchtops leading to the reservoir.

The reservoir consisted of a wooden two-compartment box lined with 0.13-mm-thick black polyethylene plastic with a total capacity of 568 liters. One compartment supplied nutrient solution to the bench while the other acted as a settling pond for returning solution and replenished the first reservoir. The nutrient solution consisted of 184 g commercially prepared 5N4.8P–2 1.6K hydroponic fertilizer (Peters Hydro-Sol; W.R. Grace and Co., Fogelsville, Pa.) and 122 g 15.5N–0P-0K dissolved in 189.2 liters water in each of the two compartments. Three separate supply lines were installed along the middle of the bench, one for each fertigation frequency. On–off leader emitters were installed in the supply lines to provide nutrient solution to individual plants in polyethylene bags. Fertigation frequencies of 12, 6, or 4 per 12-h light period were set with a 5-min cycle duration.

The root media chosen for this study were Grodan loose RW (DK 264Q Grodania A/A, Hedenhusene, Denmark), CBA, PWP, and 1 CBA :1 PWP (v/v). CBA was obtained from a local power plant and aged outdoors <6 months. PWP was obtained from a log home and rail fence manufacturer. The CBA was sieved to screen out particles >2 mm and the PWP had been ground by a Schute hammermill to pass a 1.9-cm screen.

To determine particle size distribution (PSD), five samples each of CBA and PWP were placed in a graded series of U.S. standard sieves on a horizontal shaker for 5 min. Screen sizes used were 4.76, 3.35, 2.0, 1.0, 0.5, and <0.5 mm (pan). Medium weight retained by each screen was recorded and percent total weight calculated.

Five replications of CBA, PWP, 1 CBA: 1 PWP (v/v), and RW were packed uniformly (Bilderback et al., 1982) in 7.8-cm-diameter × 7.6-cm-high polyvinylchloride cylinders. Media-filled cylinders were placed under water in desiccators, a vacuum was applied until bubbling on top of the media ceased (Klute, 1986), and the cylinders were drained for 4 h. The quantity of water drained was used as an estimate of air capacity (AC) (Buscher and VanDoren, 1973). Moisture retention curves for each medium were established by placing cylinders on porous pressure-plate extractors (Soil Moisture Equipment Co., Santa Barbara, Calif.) (DeBoodt and DeWaele, 1968; Klute, 1986) and recording moisture retained at pressures of 0.5 to 10 kPa.

Wet bulk density (WBD) equaled weight of the drained medium divided by medium volume. Dry bulk density (DBD) equaled weight of the medium after drying at 70C for 24 h divided by medium volume. Container capacity was defined as the moisture content (in grams) after drainage expressed as a percentage of medium volume (Bunt, 1976).

Media electrical conductivity (EC) was determined with a specific conductance meter (model 1052; VWRScientific,Cleveland) in 1 medium : 1 water (v/v) extracts (Rhoades, 1986).

Media pH was determined similarly (McLean, 1986) with a combination electrode (model E-5D; Fisher, Pittsburgh) attached to an expandable ion analyzer (model EA920; Orion Research, Boston).

Macro- and micronutrients were extracted from root media by the saturated medium extraction method (Warncke, 1988). Nitrate was measured with a nitrate-specific ion elec-

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trode attached to the expandable ion analyzer. All other elements were measured using an atomic absorption spectrophotometer (model 5000; Perkin-Elmer, Pittsburgh).

Media were placed in 1.89-liter black polyethylene bags (Hydro-Gardens, Colorado Springs, Colo.) with prepunched drainage holes. 'Inca Yellow' marigold seeds were germinated in 2.54-cm-wide × 2.54-cm-long × 3.8 l-cm-high RW cubes. The seedlings were transplanted to the media 24 days later, one plant per bag. Before being transplanted, the seedlings in the cubes were fertilized by flowing the nutrient solution under the cubes for 5 min three times a day.

The media-filled bags were arranged bag to bag, with media and fertigation frequencies in a split plot design and two blocks and 21 replications of each treatment per block. Guard rows were the end rows of each block. Emitters were placed one per bag.

During the crop growth cycle, concentrated H_2SO_4 was added to the nutrient solution, as required, to maintain pH at 6.0 to 6.5. The mean of solution EC was 1.47 ± 0.02 $dS \cdot m^{-1}$. When nutrient solution volume was below pump level, it was refilled to tank capacity. Lateral buds were removed from the plants to enhance the development of a single terminal flower.

When flowers were fully open, days from transplant to harvest, height from medium level to plant top, plant diameter at widest point, diameter perpendicular to the first diameter, and flower diameter were recorded. The plants were severed at medium level and top fresh weight was recorded. Approximate plant volume (V) was calculated as as $V \prod abh$, where a and b are the two radii of an ellipse and his the height.

The five most recent, fully expanded leaves were removed for elemental analysis. Entire plant tops and the leaf samples were dried to constant weight at 60C. Top dry weights included the detached leaves.

Leaves from each treatment in each of the two blocks were pooled in two groups (four replications) for analysis and ground by a laboratory mill (Arthur H. Thomas, Philadelphia) to pass through a 425-µm-pore screen. Plant tissue samples were wet-digested to determine K, Ca, Mg, Na, Fe, Cu, Zn, Mn, and Al by atomic absorption spectrophotometry. The same solution was used to determine P by a molydivanadophosphoric acid method, and optical density was read at 430 nm with an ultraviolet spectrophotometer (model 55B; Perkin-Elmer) (Greweling, 1976). Leaf samples for N analysis were pooled across fertigation frequencies, wet-ashed, and analyzed (Jones, 1977) by inductively coupled plasma emission spectroscopy (model 400; Perkin-Elmer).

At each fertigation frequency, all CBA and PWP media produced plants of similar volume (0.056 to 0.063 m^3), height (46.8 to 47.6 cm), and fresh (138.3 to 153 g) and dry (15.3 to 16.7 g) weight as those grown in RW. Flower diameters of plants in RW were significantly less than those of plants in all other media (Table 1). Time to harvest was significantly longer for plants in RW than for those in CBA, or CBA–PWP.

The 6-cycle fertigation frequency reduced plant volume, height, and fresh and dry weight below those of plants in 12- and 4-cycle frequencies, and days to harvest were increased (data not shown). We attribute this anomaly to a malfunctioning timer that caused the medium to flood.

Deleting the data for the 6-cycle frequency erased frequency as a significant factor. Accordingly, the 4- and 12-cycle frequency data were pooled and analyzed by a one-way analysis of variance comparing the four media.

Values for pH were higher in RW than in the other media, in spite of our efforts to maintain the nutrient solution pH at 6.0 to 6.5 (Table 2). RW had lower EC values than PWP or CBA–PWP, but not CBA. The CBA–PWP mix had the highest EC and contained more water-soluble NO_3 than RW or PWP. RW and CBA yielded similar amounts of water-soluble NO_3, P, K, and Mg, but CBA was higher in Ca. CBA–PWP retained more water-soluble K, Ca, and Mg than CBA or PWP alone. PWP may release humic materials that may have solubilized additional K, Ca, and Mg from CBA (Schnitzer, 1982). The fact that PWP released more water-soluble P than any other medium also may be due to the action of humic materials in PWP. The solubilization of P in CBA–PWP may have been reduced by an interaction with Ca from CBA (Tisdale and Nelson, 1956).

Leaf analyses (Table 3) indicated that marigolds growing in all media accumulated similar amounts of N, P, K, Ca, Mg, Fe, Na, and Al, and the concentrations we obtained (data not shown) were similar to those reported by Nelson (199 1), except that P levels were higher (0.70 to 0.75 vs. a recommended 0.3%) in plants in all media. Plants in CBA–PWP accumulated less Cu than plants in CBA. Plants in PWP and CBA–PWP accumulated less Zn than plants in RW or CBA. Plants in CBA–PWP accumulated less Mn than plants in PWP. In all media, foliar micronutrient levels were much higher than recommended (Nelson, 199 1), perhaps due to their release from media in addition to those supplied by the nutrient solution.

CBA WBD (Table 4) was excessive when compared with the range listed by Nelson (1991). Mixing CBA with the much lighter PWP lowered the WBD of the mix to just above the recommended range. RW and CBA air capacities were below range, while PWP AC was above the range. CBA–PWP had an AC just within the lower part of the range. RW, CBA, and CBA–PWP container capacities were excessive.

CBA contained a higher percentage of particles retained by the 4.76- and 0<.5-mm sieve categories (Table 5) than PWP, and PWP retained more particles in the 2.0-and 1.0-mm sieves than CBA. Values for CBA–PWP in general were intermediate, except for those in the 0.5- and <0.5 -mm categories. The very low percentage of <0.5-mm-diameter particles in PWP may have had minimal effect on PSD when mixed with CBA. CBA and PWP values of 0.5-mm particles may have been close enough so that no change in PSD took place in CBA-PWP.

The amount of easily available water (i.e., moisture retained between 0.5 and 5 kPa) (DeBoodt and DeWaele, 1968) was highest as a percentage of volume in RW (Fig. 1). Easily available CBA, PWP, and CBA–PWP water curves fell close to each other and considerably below that of RW. RW water buffer capacity (5 to 10 kPa) also was much higher than that of the other media.

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Table 1. Growth and flowering of 'Inca Yellow' marigolds in response to four media rockwool (RW), coal bottom ash (CBA), pine wood peelings (PWP), or 1 CBA :1 PWP (v/v).

Medium	Flower diam (cm)	Days to harvest
RW	11.3b[z]	58.5 a
CBA	12.2 a	56.3 b
PWP	12.2 a	57.6 ab
CBA-PWP	12.6 a	56.3 b

[z]Mean separation within columns by Duncan's multiple range test, $P \leq 0.05$.

Table 2. Saturated paste-extractable pH, electrical conductivity (EC), and elements in rockwool (RW), coal bottom ash (CBA), pine wood peelings (PWP), and 1 CBA: 1 PWP (v/v) after their use as marigold root media in a circulating nutricuiture system.

Medium	pH	EC ($dS \cdot m^{-1}$)	NO_3-N	P	K	Ca	Mg
			($mg \cdot liter^{-1}$)				
RW	7.6 a[z]	0.60 **C**	32.5 b	8.5 **C**	11Oc	28.0 **C**	15.0 c
CBA	6.85 b	1.18bc	56.5 ab	7.5 c	168 c	94.0 b	31.0bc
PWP	7.10 b	1.75 b	11.0b	47.0 a	322 b	90.0 b	46.0 b
CBA-PWP	6.80 b	3.18 a	119.0a	29.5 b	545 a	167.0 a	83.0 a

[z]Mean separation within columns by Duncan's multiple range test, $P \leq 0.05$.

Table 3. Foliar minor element content (in ppm) of 'Inca Yellow' marigolds grown in rockwool (RW), coat bottom ash (CBA), pine wood peelings (PWP), or 1 CBA :1 PWP (v/v) in a circulating nutriculture system.

Medium	Fe	Cu	Zn	Mn
RW	285 a[z]	18.03 ab	46.53 a	290 ab
CBA	370 a	18.49 a	48.52 a	275 ab
PWP	270 a	16.97 ab	35.63 b	328 a
CBA-PWP	188 a	14.68 b	36.00 b	249 b

[z]Mean separation within columns by Duncan's multiple range test, $P \leq 0.05$.

Table 4. Physical characteristics of rockwool (RW), coal bottom ash (CBA), pine wood peelings (PWP), and 1 CBA :1 PWP (v/v) used as components of root media in a circulating nutriculture system.

Medium	WBD[z] ($g\cdot cm^{-3}$)	Percent medium Vol[y] AC	CC	TPS
RW	1.06	8.8	89.5	98.3
CBA	1.36	5.0	61.0	66.0
PWP	0.63	37.0	49.9	86.9
CBA-PWP	1.24	10.9	61.9	72.8
RR[x]	0.64-1.2	10-20	35-50	
LSD[w]	0.07	4.7	6.8	4.3

[z]WSD = wet bulk density.
[y]AC = air capacity CC = container capacity; TPS = total pore space.
[x]Recommended range (Nelson, 1991).
[w]Mean separation within columns by Fisher's least significant difference at $P < 0.05$.

Table 5. Particle distribution (percent by weight of total sieved) of coal bottom ash (CBA), pine wood peelings (PWP), and 1 CBA: 1 PWP (v/v) used as components of root media in a circulating nutriculture system.

Medium	Sieve aperture size (mm) 4.76	3.35	2.0	1.0	0.5	<0.5
			Percent			
CBA	29.4[z]	9.9	14.2	16.5	10.1	19.8
PWP	8.9	12.1	26.4	34.7	12.9	5.1
CBA–PWP	18.5	11.5	18.9	20.8	9.8	20.5
LSD[z]	5.2	NS	3.0	3.6	2.4	7.2

[z]Mean separation within columns by Fisher's least significant difference at $P \leq 0.05$; NS = nonsignificant.

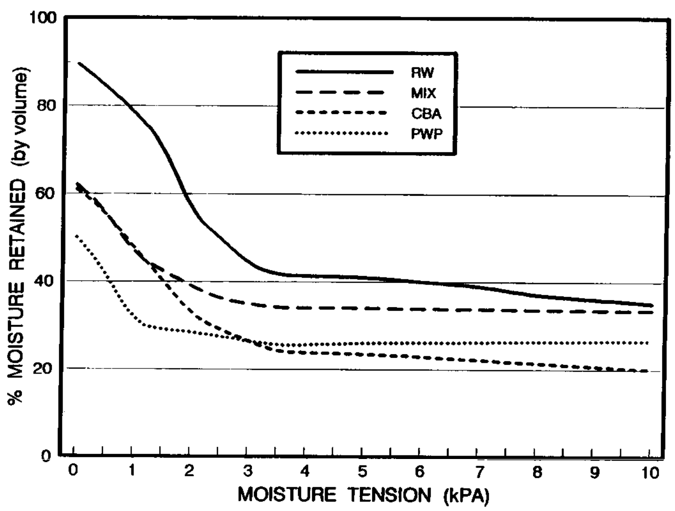

Fig. 1. Moisture retention curves for rockwool (RW), coal bottom ash (CBA), pine wood peelings (PWP). and 1 CBA : 1 PWP (v/v) used as components of root media in a circulating nutriculture system.

flower diameter of plants grown in RW compared to those of plants in the other media may be a consequence of excessive hydration of RW, a root medium with container capacity nearly 50% higher than that of CBA or CBA–PWP and a low AC. The high percentage of RW easily available water also indicates that a lower fertigation frequency might have improved marigold performance in this medium.

According to Cluskey (1989), marigold growth and flowering in a nutriculture system was generally inferior in CBA and PWP compared to those of plants in a peat–vermiculite control when fertigation frequency was set at one cycle/day. Inadequate moisture and nutrient availability were cited as causes for poor plant performance. The present investigation demonstrates that 5-min fertigation frequencies 4 to 12 times per 12-h day produced marigolds in CBA and PWP similar to those produced in RW in the same nutriculture system.

The system described in this investigation is a miniature (10 m^2) representation of existing commercial recycling systems (Nelson, 1991). Producing marigolds in such a system seems feasible, although effects on postproduction performance require further study. The configuration of our system, which allows isolated irrigation regimes, and the randomization of several treatments within these permits further research and development of nutriculture techniques.

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