The pH, Electrical Conductivity, and Primary Macronutrient Concentration of Sphagnum Peat and Ground Parboiled Fresh Rice Hull Substrates Over Time in a Greenhouse Environment

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SUMMARY. The primary objective of this research was to compare the pH, electrical conductivity (EC), and primary macronutrient status of three ground parboiled fresh rice hull (PBH) products to sphagnum peat when used as a root substrate over 56 days in a greenhouse environment. The three grades of ground rice hull products were produced by grinding PBH and passing the ground product through different screens. One grade (P3) was passed through a 2.00-mm screen and captured on a 1.00-mm screen. The second grade (P4) was passed through a 1.00-mm screen and captured on 0.50-mm screen. A third ground rice hull product (RH3) was a commercially available, ground PBH material that was ground in a hammer mill until it passed through a screen with 1.18-mm-diameter openings and was collected on a screen with 0.18-mm openings. The pH of sphagnum peat ranged from 3.4 to 3.7 across time. The pH of RH3 and P3 increased from 4.7 to 7.1 on day 5 and 14, respectively, before decreasing to 6.3 and 6.7, respectively, on day 56. The pH of P4 increased from 4.8 to 6.9 on day 6 before decreasing to 6.6 on day 56. The P4 had an EC of 1.2 dS·m⁻¹, which was higher than that of peat, RH3, and P3, which had similar EC of 0.7 to 0.8 dS·m⁻¹ regardless of time. The ammonium (NH₄⁺) concentration was unaffected by time. Peat had an NH₄⁺ concentration of 6.4 mg·L⁻¹, which was lower than that of the ground rice hull products. The P3 had an NH₄⁺ concentration of 14.6 mg·L⁻¹, which was higher than that of RH3 and P4. The RH3 and P4 had similar NH₄⁺ concentrations of 11.8 and 10.8 mg·L⁻¹, respectively. The nitrate (NO₃⁻) concentration was unaffected by time. The RH3 had a NO₃⁻ concentration of 8.2 mg·L⁻¹, which was significantly higher than that of peat, P3, and P4, which had similar NO₃⁻ concentrations of 0.5 mg·L⁻¹. The phosphorus (P) concentration in peat ranged from 1.3 to 2.5 mg·L⁻¹ across the sampling times, and peat had a lower P concentration than all rice hull products, which ranged from 57.4 to 104.4 mg·L⁻¹. The potassium (K) concentration in peat ranged from 2 to 5 mg·L⁻¹ across the sampling times and was always lower than that of the rice hull products, which had a K concentration ranging from 195 to 394 mg·L⁻¹. Because pH, P, and K concentrations were above recommended concentrations, ground rice hull products would not be suitable as a stand-alone substrate but might be amended with materials such as elemental sulfur or iron sulfate to adjust the pH or blended with other components to reduce the P and K concentrations to within recommended concentrations.

Root substrates may be composed of a single component or they may be composites that contain multiple components blended together to provide suitable physical and chemical properties as

required by the specific crop and cultural conditions (Bunt, 1988; Nelson, 1998). One of the most common materials used in the formulation of substrates is sphagnum peat (peat). Environmental concerns (Barkham,

1993; Buckland, 1993; Robertson, 1993) in the European Union and cost in markets, such as Japan, that are far from commercial sphagnum peat sources have generated significant interest in the development of new components that could serve a similar role as peat in substrates. Additionally, an emphasis on sustainability has increased interest in finding uses for agricultural and municipal by-products. One of the potential areas in which such by-products might be used is as horticultural substrate components.

Most research on the development of new substrate components has been focused on agricultural, industrial, and municipal by-products. Among these products were coconut coir (Evans et al., 1996), cotton gin trash (Wang, 1991), waste paper products (Chong and Cline, 1993), composted rice hulls (Laiche and Nash, 1990), kenaf (Wang, 1994), composted yard waste (Beeson, 1996), ground feather fiber (Evans, 2004b), clean chip residual (Boyer et al., 2008; Wright et al., 2008), and various composted animal manures (Li et al., 2009). While some of these materials have been successfully used, some were not produced in large enough quantities to impact the market, some were too expensive for their intended use, some had a high degree of variability, and some had a high likelihood of containing contaminants such as weed seeds, metal fragments, or glass (Beeson, 1996; Hartz et al., 1996). Other potential substrate components had chemical properties that made them unsuitable for use as a substrate component. For example, ground rubber tires contained levels of zinc that were phytotoxic to some greenhouse crops (Evans and Harkess, 1997). Neal and Wagner (1983) reported of finding high levels of lead in coal cinders used as a root substrate. Vermicompost produced from bovine or porcine manure were found to possess excessively high plant-available nutrients (Bachman

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
29.5735	fl oz	mL	0.0338
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
1	mmho/cm	dS·m ⁻¹	1
1	ppm	mg·L ⁻¹	1
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

and Metzger, 2007). Evans (2004a) reported that ground bovine bone yielded high levels of ammonia (NH_3) when used in peat-based substrates and ground poultry feathers produced high levels of NH_4^+ (Evans, 2004b).

Rice is produced in many areas of the world and in the United States extensively in Arkansas, California, Mississippi, and Texas. Rice hulls are the by-product of the rice milling industry and consist mainly of hemicellulose, lignin, and 20% (by weight) amorphous silica (Juliano et al., 1987). Kamath and Proctor (1998) estimated that 34 million tons of fresh rice hulls were produced annually in the United States.

Sambo et al. (2008) reported the physical properties of various ground non-PBH. No fresh ground rice hull products passed through 1-, 2-, 4-, or 6-mm-diameter screens had the same physical properties as peat, but some of the products had physical properties within recommended ranges. Buck and Evans (2010) reported that ground PBH passed through a 1.18-mm screen and collected on a 0.18-mm screen had a similar total pore space, air-filled pore space, and water-holding capacity as a sphagnum peat. Several other ground rice hull products, although different from the sphagnum peat, had physical properties that were within acceptable ranges for substrate components.

Although researchers have reported on results to demonstrate that various ground rice hull products had suitable physical properties for use in substrates, no information has been reported on the chemical properties of ground PBH products or if their chemical properties were within the acceptable ranges to allow them to be suitable for use as substrate components. The objectives of this research were to determine and compare the substrate pH, EC, and primary macronutrient status of three ground PBH products to sphagnum peat over time in a greenhouse environment and to determine if these chemical properties were within acceptable ranges for use in substrates.

Materials and methods

Sphagnum peat was obtained from Sun Gro Horticulture (Bellevue, WA). The PBH was obtained from Riceland Foods (Stuttgart, AR) and was used to produce two grades of ground rice hulls at the University of Arkansas,

Fayetteville, AR. For both grades, the PBH was ground through a rotary Wiley mill (CSC Scientific, Fairfax, VA) using a diamond-shaped 5-mm-wide $\times$ 8-mm-high screen. One grade (P3) was ground PBH that passed through a 2.00-mm screen and was captured on a 1.00-mm screen. The second grade (P4) was ground PBH that passed through a 1.00-mm screen and was captured on 0.50-mm screen. A third ground rice hull product (RH3) was a commercially available ground PBH material (Riceland Foods) that was ground in a hammer mill until it passed through a screen with 1.18-mm-diameter openings and was collected on a screen with 0.18-mm openings. These grades of ground PBH were used because they had been previously shown to have physical properties within recommended ranges for use as a substrate (Buck and Evans, 2010).

The sphagnum peat and ground rice hull products were adjusted to 50% (by weight) moisture with deionized water, placed in separate plastic bags, and allowed to equilibrate for 24 h. Each material was then placed into 4.5-inch plastic containers. Containers were transferred to a glass-glazed greenhouse. Air temperatures were maintained between 18 and 24 °C under ambient light levels (350–525 $\mu\text{mol}\cdot\text{s}^{-1}\cdot\text{m}^{-2}$ at 1200 HR). The substrates in each container were maintained moist, but without leaching, by

applying 50 mL of deionized water to the surface of the substrate daily. Plants were excluded and the containers were irrigated with deionized water without leaching to remove confounding factors and to allow a determination of only the differences attributed to the substrate components.

Substrate samples were taken after 0 (after initial mixing), 1, 2, 3, 4, 5, 6, 7, 14, 28, 42, and 56 d in the greenhouse environment. The substrate pH, EC, and the primary macronutrient concentrations were determined using the saturated media extract method as outlined by the North Central Regional Committee for Soil and Plant Analysis (Warncke, 1988). EC was determined using an EC meter (model 441; Corning, Corning, NY) and the pH was determined using a pH meter (model AB 15; Fisher Scientific, Pittsburgh, PA). The NH_4^+ was determined by the nitroprusside-salicylate procedure (Wall et al., 1975), and the NO_3^- concentration was determined using the copperized cadmium reduction procedure (Keeney and Nelson, 1982). The concentrations of P and K were determined using the filtered extract for simultaneous inductively coupled plasma emission spectrometry (Jones, 1977; Munter and Grande, 1981). A container served as a replication and was used for a single sampling time. There were five replications per substrate and sampling time.

Fig. 1. The pH of sphagnum peat and ground rice hull substrates over time. The RH3 rice hull product was parboiled fresh rice hulls (PBH) ground and passed through a 1.18-mm screen and collected on a 0.18-mm screen. The P3 and P4 materials were ground PBH with a particle size of 1.00–2.00 mm and 0.5–1.0 mm, respectively. Component and time were significant at $P = 0.001$. Symbols represent the means and curves represent predicted values based on the regression models. Models for equations were as follows: peat $\text{pH} = 3.539 - 0.0092x$ ($R^2 = 0.11$), RH3 $\text{pH} = 3.51 + 0.93x - 0.06x^2$ ($R^2 = 0.95$), P3 $\text{pH} = 3.89 + 0.72x - 0.04x^2$ ($R^2 = 0.97$), and P4 $\text{pH} = 4.70 - 0.19x + 0.23x^2 - 0.03x^3$ ($R^2 = 0.99$). The *** indicate that the means at each point in time were significantly different at $P = 0.001$; 1 mm = 0.0394 inch.

An analysis of variance was conducted to determine if significant differences occurred in substrate pH, EC, or primary macronutrient concentrations as a result of component and time. Where component and time were significant, regression analysis was conducted to develop models that described the change in the variable for each component over time. Additionally, the slice option in SAS (version 9.1; SAS Institute, Cary, NC) was used to determine if significant differences occurred among the components at specific times. Where time was not significant, the data were pooled across time and an analysis of variance was conducted to determine if there were significant differences among the components, and where significant differences occurred, a least significant difference mean separation test was conducted to determine specific differences between components.

Results and discussion

Component and time had a significant effect on substrate pH (Fig. 1). Peat had a lower pH than all the ground rice hull products at all sampling times and decreased linearly over time from 3.7 to 3.4. The pH was similar for the three ground rice hull products at all sampling times except on days 1, 2, and 5 when RH3 had a higher pH than P3. The pH of RH3 and P3 over time followed a second-order polynomial function and increased to 7.1 on days 5 and 14, respectively, before decreasing on day 28. The pH of P4 followed a third-order polynomial function and increased to 6.9 on day 6 before decreasing on day 28 and leveling off on day 42.

Sampling time did not affect EC, and so the data for EC were pooled across time (Fig. 2). The ground rice hull product P4 had an EC of $1.2 \text{ dS}\cdot\text{m}^{-1}$, which was higher than that of peat, RH3, and P3. Peat, RH3, and P3 had a similar EC, which ranged from 0.7 to $0.8 \text{ dS}\cdot\text{m}^{-1}$.

Sampling time did not affect NH_4^+ concentration, and so the data were pooled across time (Fig. 2). Peat had an NH_4^+ concentration of $6.4 \text{ mg}\cdot\text{L}^{-1}$, which was lower than that of all the ground rice hull products. The ground rice hull product P3 had an NH_4^+ concentration of $14.6 \text{ mg}\cdot\text{L}^{-1}$, which was higher than that of RH3 and P4, which had similar NH_4^+ concentrations

Fig. 2. The (A) electrical conductivity (EC) and (B) ammonium (NH_4^+) and nitrate (NO_3^-) concentration of sphagnum peat and ground rice hull substrates. The RH3 rice hull product was parboiled fresh rice hulls (PBH) ground and passed through a 1.18-mm screen and collected on a 0.18-mm screen. The P3 and P4 materials were ground PBH with a particle size of 1.00–2.00 mm and 0.5–1.0 mm, respectively. Time was not significant, so data were pooled across time. Component was significant at $P = 0.001$. Error bars represent the global least significant difference values of $0.13 \text{ dS}\cdot\text{m}^{-1}$, $2.8 \text{ mg}\cdot\text{L}^{-1}$, and $1.8 \text{ mg}\cdot\text{L}^{-1}$ for EC, NH_4^+ , and NO_3^- , respectively ($\alpha = 0.05$); 1 mm = 0.0394 inch, $1 \text{ dS}\cdot\text{m}^{-1} = 1 \text{ mmho}/\text{cm}$, $1 \text{ mg}\cdot\text{L}^{-1} = 1 \text{ ppm}$.

of 11.8 and 10.8 mg·L⁻¹, respectively. Sampling time did not affect NO₃⁻ concentration, and so the data were pooled across time (Fig. 2). The RH3 product had a NO₃⁻ concentration of 8.2 mg·L⁻¹, which was significantly higher than that of peat, P3, and P4, which had similar NO₃⁻ concentrations of 0.5 mg·L⁻¹.

Component and time had a significant effect on P concentration (Fig. 3). Although fifth- and sixth-order polynomial models could be fit to the changes in P over time for the different components, the models had no biological significance and are therefore not shown. The P concentration in peat ranged from 1.3 to 2.5 mg·L⁻¹ across the sampling times, and at all sampling times, peat had a lower P concentration than all the rice hull products. The P concentration of P4 ranged from 57.4 to 75.5 mg·L⁻¹ across sampling times and was lower than the P concentrations of RH3 and P3, which ranged from 70.4 to 104.4 and 79.0 to 134.2 mg·L⁻¹, respectively. Except for days 4, 14, and 42, P3 had a higher P concentration than RH3.

Component and time had a significant effect on K concentration (Fig. 4). The K concentrations in rice hull products decreased over time, and although fifth- and sixth-order polynomial models could be fit to the changes in P over time for the different components, the models had no biological significance and are therefore not shown. The K concentration in peat ranged from 2 to 5 mg·L⁻¹ across the sampling times, and at all sampling times, peat had a lower K concentration than all rice hull products. Across all times, rice hull products had a K concentration of 195 to 394 mg·L⁻¹. At some sampling times, P3 had a higher K concentration than RH3 and P4. At most sampling times, RH3 and P4 had similar K concentrations.

Evans and Gachukia (2008) reported that substrates containing whole PBH had a higher pH than equivalent perlite-containing substrates. They attributed the difference in substrate pH to the fact that rice hulls contained 20% silica (Kamath and Proctor, 1998) and that silicates acted as bases and could have caused the substrate pH to increase. This reasoning may also be one explanation as to why ground rice hull substrates always had a higher pH than sphagnum peat

Fig. 3. The phosphorus (P) concentration of sphagnum peat and ground rice hull substrates over time. The RH3 rice hull product was parboiled fresh rice hulls (PBH) ground and passed through a 1.18-mm screen and collected on a 0.18-mm screen. The P3 and P4 materials were ground PBH with a particle size of 1.00–2.00 mm and 0.5–1.0 mm, respectively. Component and time were significant at $P = 0.001$ and the *** indicate that the means at each point in time were significant at $P = 0.001$; 1 mm = 0.0394 inch, 1 mg·L⁻¹ = 1 ppm.

Fig. 4. The potassium (K) concentration of sphagnum peat and ground rice hull substrates over time. The RH3 rice hull product was parboiled fresh rice hulls (PBH) ground and passed through a 1.18-mm screen and collected on a 0.18-mm screen. The P3 and P4 materials were ground PBH with a particle size of 1.00–2.00 mm and 0.5–1.0 mm, respectively. Component and time were significant at the 0.001 levels, and the *** indicate that the means at each point in time were significant at $P = 0.001$; 1 mm = 0.0394 inch, 1 mg·L⁻¹ = 1 ppm.

and why pH increased in the ground rice hull substrates until about day 5 before becoming stable and then decreasing. The grinding process could have released silicates from the rice hull, making them rapidly available, which caused pH to increase over time. The remaining silicates would have been bound in the rice hull particles and more slowly released into the substrate solution by microbial activity. The slower rate of release of silicates may not have been enough to result in a further increase in substrate pH.

The highest pH of RH3, P3, and P4 was 7.1, 7.1, and 6.9, respectively. These values exceeded the generally recommended pH ranges of ≈ 5.5 to 6.5 for most greenhouse crops (Argo and Fisher, 2002; Fonteno et al., 1996; Lucas et al., 1975; Raviv and Lieth, 2008; Reed, 1996; Robbins and Evans, 2005). Therefore, if used as single component substrates, the pH of ground rice hull products could be problematic and would likely need to be adjusted either by incorporating a material such as elemental sulfur,

aluminum sulfate, or iron sulfate to lower the pH. Additionally, the ground rice hull products could be blended with another acidic substrate component such as sphagnum peat to produce a composite substrate with an acceptable pH.

Although differences occurred among the peat and ground rice hull products for EC, NH_4^+ , and NO_3^- , the range in values for these variables was only $0.4 \text{ dS}\cdot\text{m}^{-1}$, $7 \text{ mg}\cdot\text{L}^{-1}$, and $7.5 \text{ mg}\cdot\text{L}^{-1}$, respectively. Additionally, the levels of these variables were within commonly recommended ranges of up to $2 \text{ dS}\cdot\text{m}^{-1}$, $20 \text{ mg}\cdot\text{L}^{-1}$, and $199 \text{ mg}\cdot\text{L}^{-1}$ for EC, NH_4^+ , and NO_3^- , respectively, for greenhouse crops (Argo and Fisher, 2002; Fonteno et al., 1996; Lucas et al., 1975; Raviv and Lieth, 2008; Reed, 1996; Robbins and Evans, 2005). Therefore, the differences that occurred were not of practical significance.

Cadell (1988) reported that fresh rice hulls contained $34 \text{ mg}\cdot\text{kg}^{-1}$ P and $5010 \text{ mg}\cdot\text{kg}^{-1}$ K on a dry weight basis. Orthoefer and Eastman (2004) also reported that rice bran contained high concentrations of P and K. The high levels of P and K in the rice hulls could explain why all ground rice hull products had P and K levels higher than those of peat. These results were similar to those reported by Evans and Gachukia (2008), who also reported that peat-based substrates amended with whole PBH had higher P and K levels than equivalent substrates amended with perlite. The P and K levels of all the ground rice hull products were above the generally recommended levels of up to $10 \text{ mg}\cdot\text{L}^{-1}$ and $200 \text{ mg}\cdot\text{L}^{-1}$ for P and K, respectively, (Argo and Fisher, 2002; Fonteno et al., 1996; Lucas et al., 1975; Raviv and Lieth, 2008; Reed, 1996; Robbins and Evans, 2005) and could be problematic for greenhouse crop production and preclude ground rice hull products from being used as single component substrates. However, the ground rice hull products could be blended with other components such as sphagnum peat or composted bark that are lower in P and K to produce a composite material with an acceptable P and K level. If blended with sphagnum peat, a composite material could potentially be produced with an acceptable pH and acceptable P and K levels.

Conclusions

Regardless of particle size, all ground rice hull products had EC, NH_4^+ , and NO_3^- concentrations that were not excessively high and within recommended ranges for use as a greenhouse crops root substrate. However, the pH and the P and K concentrations of ground rice hull products were higher than those of sphagnum peat and higher than recommended levels. If used in a production system where little or no leaching occurred, the higher than recommended pH and P and K levels would be problematic for using ground rice hulls products from being used as single component substrates and would require substrate manufacturers and greenhouse managers to take steps to address the high pH and P and K levels. If used as single component substrates, the pH of ground rice hull products could be adjusted with the addition of elemental sulfur, aluminum sulfate, or iron sulfate to lower the pH. Ground rice hull products could be blended with an acidic substrate component such as sphagnum peat to produce a composite substrate with an acceptable pH. The P and K levels could also be adjusted by blending the ground rice hull products with other components such as sphagnum peat or composted bark that are lower in P and K to produce a composite material with an acceptable P and K level.

Literature cited

Argo, W.R. and P.R. Fisher. 2002. Understanding pH management for container-grown crops. Meister Publ, Willoughby, OH.

Bachman, G.R. and J.D. Metzger. 2007. Physical and chemical characteristics of a commercial potting substrate amended with vermicompost produced from two different manure sources. *HortTechnology* 17:336–340.

Barkham, J.P. 1993. For peat's sake: Conservation or exploitation? *Biodivers. Conserv.* 2:556–566.

Beeson, R.C. Jr. 1996. Composted yard waste as a component of container substrates. *J. Environ. Hort.* 14:115–121.

Boyer, C.R., G.B. Fain, C.H. Gilliam, T.V. Gallagher, H.A. Torbert, and J.L. Sibley. 2008. Clean chip residual: A substrate component for growing annuals. *HortTechnology* 18:423–432.

Buck, J.S. and M.R. Evans. 2010. Physical properties of ground parboiled fresh rice hulls used as a horticultural root substrate. *HortScience* 45:643–649.

Buckland, P. 1993. Peatland archaeology: A conservation resource on the edge of extinction. *Biodivers. Conserv.* 2:513–527.

Bunt, A.C. 1988. Media and mixes for container-grown plants. Unwin Hyman, London.

Cadell, M. 1988. Rice hull composting in Australia. *Biocycle* 29:49.

Chong, C. and R.A. Cline. 1993. Response of four ornamental shrubs to container substrate amended with two sources of raw paper mill sludge. *HortScience* 28:807–809.

Evans, M.R. 2004a. Ground bovine bone as a perlite alternative in horticultural substrates. *HortTechnology* 14:171–179.

Evans, M.R. 2004b. Processed poultry feather fiber as an alternative to peat in greenhouse crops substrates. *HortTechnology* 14:176–179.

Evans, M.R. and M. Gachukia. 2008. Root substrate pH, electrical conductivity, and macroelement concentration of sphagnum peat-based substrates amended with parboiled fresh rice hulls or perlite. *HortTechnology* 18:644–649.

Evans, M.R. and R.L. Harkess. 1997. Growth of *Pelargonium xhortorum* and *Eurphorbia pulcherrima* in rubber-containing substrates. *HortScience* 32:874–877.

Evans, M.R., S. Konduru, and R.H. Stamps. 1996. Source variation in physical and chemical properties of coconut coir dust. *HortScience* 31:965–967.

Fonteno, W.C., P.V. Nelson, and D.A. Bailey. 1996. Testing procedures for bedding plants. *North Carolina Flower Growers' Bul.* 41:1–23.

Hartz, T.K., F.J. Costa, and W.L. Schrader. 1996. Suitability of composted green waste for horticultural uses. *HortScience* 31:961–964.

Jones, J.B. Jr. 1977. Elemental analysis of soil extracts and plant tissue ash by plasma emission spectroscopy. *Commun. Soil Sci. Plant Anal.* 8:345–365.

Juliano, B., C. Maningat, and C. Pascual. 1987. Properties of fraction of rice hull. *Phytochemistry* 26:3261–3263.

Kamath, S. and A. Proctor. 1998. Silica gel from rice hull ash: Preparation and characterization. *Cereal Chem.* 75:484–487.

Keeney, D.R. and D.W. Nelson. 1982. Nitrogen: Inorganic forms, p. 643–698.

- In: W.C. Dahnke (ed.). *Methods of soil analysis*. Part 2, 2nd ed. Amer. Soc. Agron., Madison, WI.
- Laiche, A.J. and V.E. Nash. 1990. Evaluation of composted rice hulls and a lightweight clay aggregate as components of container-plant growth media. *J. Environ. Hort.* 8:14–18.
- Li, Q., J. Chen, R.D. Caldwell, and M. Deng. 2009. Cowpeat as a substitute for peat in container substrates for foliage plant production. *HortTechnology* 19: 340–345.
- Lucas, R.E., P.E. Rieke, J.C. Shickluna, and A. Cole. 1975. Lime and fertilizer requirements for peats, p. 51–70. In: D.W. Robinson and J.G.D. Lamb (eds.). *Peat in horticulture*. Academic Press, London.
- Munter, R.C. and R.A. Grande. 1981. Plant tissue and soil extract analysis by ICP-atomic emission spectrometry, p. 653–672. In: R.M. Barnes (ed.). *Developments in atomic plasma spectrochemical analysis*. Heyden and Sons, London.
- Neal, J.C. and D.F. Wagner. 1983. Physical and chemical properties of coal cinders as a container media component. *HortScience* 18:693–695.
- Nelson, P.V. 1998. *Greenhouse operation and management*, 5th ed. Prentice Hall, Upper Saddle River, NJ.
- Orthoefer, F.T. and J. Eastman. 2004. Rice bran and oil, p. 572. In: E.T. Champagne (ed.). *Rice: Chemistry and technology*. American Assn. Cereal Chemists, St. Paul, MN.
- Raviv, M. and J.H. Lieth. 2008. *Soilless culture: Theory and practice*, 1st ed. Elsevier, London.
- Reed, D.M. 1996. Alkalinity, pH and acidification, p. 69–86. In: D.M. Reed (ed.). *Water, media and nutrition for greenhouse crops*. Ball Publ, Batavia, IL.
- Robbins, J.A. and M.R. Evans. 2005. *Growing media for container production in a greenhouse or nursery: Part II (Physical and chemical properties)*. Univ. Arkansas Coop. Ext. Serv. FSA6097-PD-4-05R.
- Robertson, R.A. 1993. Peat, horticulture and environment. *Biodivers. Conserv.* 2:541–547.
- Sambo, P., F. Sannazzaro, and M. Evans. 2008. Physical properties of ground fresh rice hulls and sphagnum peat used for greenhouse root substrates. *HortTechnology* 18:384–388.
- Wall, L.L., C.W. Gehrke, T.E. Neuner, R.D. Cathey, and P.R. Rexroad. 1975. Total protein nitrogen: Evaluation and comparison of four different methods. *J. Assn. Offic. Anal. Chem.* 58:811–817.
- Wang, Y. 1991. Evaluation of media consisting of a cotton waste for the production of tropical foliage species. *J. Environ. Hort.* 9:112–115.
- Wang, Y. 1994. Using ground kenaf stem core as a major component of container media. *J. Amer. Soc. Hort. Sci.* 119:931–935.
- Warncke, D. 1988. Recommended test procedure for greenhouse growth media, p. 34–37. In: W.C. Dahnke (ed.). *Recommended chemical soil test procedures for the north central region*. North Dakota Agr. Expt. Sta. Bul. 499.
- Wright, R.D., B.E. Jackson, J.F. Browder, and J.G. Latimer. 2008. Growth of chrysanthemum in a pine tree substrate requires additional fertilizer. *HortTechnology* 18:111–115.