

Article

Reducing Anion Nutrient Leaching Losses from a Short-Cycle Container-Grown Crop (*Tagetes patula*) Using Activated Aluminum

Damon E. Abdi ^{1,*} , Jennifer Blanchard ², Jeb S. Fields ¹ , Leticia Santos ², Lily Beasley ³ and Jeffrey Beasley ²

¹ Hammond Research Station, Louisiana State University Agricultural Center, 21549 Old Covington Highway, Hammond, LA 70403, USA

² School of Plant, Environmental, and Soil Sciences, Louisiana State University Agricultural Center, 226 J.C. Miller Hall, Baton Rouge, LA 70803, USA

³ Independent Researcher, 600 West Arlington Blvd., Greenville, NC 27834, USA

* Correspondence: dabdi@agcenter.lsu.edu

Abstract: Short-cycle horticulture crops often rely on fertigation to provide immediately available nutrients. This practice poses an environmental threat when nutrients, particularly phosphorus, leach from containers and enter waterways. One method that could be used to reduce the loss of phosphorus and other key anions from horticultural crops is incorporating activated aluminum into container substrates. This study investigates the incorporation of three rates of activated aluminum into a pine bark substrate, and the effects this amendment may have on the container leachate nutrient content and the growth of a popular short-cycle crop (*Tagetes patula*, French marigold). The addition of activated aluminum reduced the cumulative mass of phosphorus in container leachate by 69–96% compared to a standard pine bark substrate. The growth index and subjective plant quality scores of *Tagetes* were equivalent between the activated aluminum-amended substrates and pine bark only substrates, in all cases, producing a salable, quality crop. This study demonstrates that incorporating activated aluminum into container substrates is an effective way to reduce phosphorus loss to the environment without sacrificing crop quality.

Keywords: container-crop; fertigation; fertilizer; floriculture; leachate; phosphorus; *Tagetes*



Citation: Abdi, D.E.; Blanchard, J.; Fields, J.S.; Santos, L.; Beasley, L.; Beasley, J. Reducing Anion Nutrient Leaching Losses from a Short-Cycle Container-Grown Crop (*Tagetes patula*) Using Activated Aluminum.

Agriculture **2023**, *13*, 1028.

<https://doi.org/10.3390/agriculture13051028>

Academic Editor: Rosario Paolo Mauro

Received: 6 April 2023

Revised: 4 May 2023

Accepted: 5 May 2023

Published: 9 May 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Fertilizers are applied in the nursery industry to accelerate plant growth to produce larger, salable plants within shorter production cycles [1]; however, the nutrients applied to container-grown plants are prone to movement, particularly if the plants are grown in organic substrates with low nutrient and water-holding capacities [2–5] and subject to high irrigation and/or precipitation volumes [6–8]. The offsite movement of fertilizers applied in agricultural operations are a concern because nutrients from these sources have been identified as contributing to surface water impairment [9].

Concerns for environmental stewardship have led the greenhouse and nursery industries to develop and refine the best management practices (BMP) to reduce offsite nutrient movement [9,10]. The current nutrient best management practices (BMP) include altering nutrient sources to use less soluble, slowly available forms [7,11–13], properly timing fertilizer applications [14], reducing fertilizer application rates [15,16], applying fertilizers with appropriate N and P ratios [17], reducing container leaching and runoff volumes via improved irrigation application methods and timing [6,18], and capturing runoff for treatment or recycling [19–22]. However, implementing nutrient BMP can be difficult or cost-prohibitive when growing short-cycle crops due to nutrient availability concerns during abbreviated production schedules. For example, Sanders and Beasley [23] found that controlled-release fertilizers (CRF) were an acceptable alternative to water-soluble

fertilizers (WSF) to reduce P leaching during a 56-day coleus (*Plectranthus scutellarioides* (L.) Codd.) production cycle, but noted that CRF-coleus lagged in growth versus WSF-coleus in the first 28 days after planting. These results emphasize grower concerns that implementing nutrient BMP could negatively impact the growth of short-cycle crops or extend the period of production to increase costs.

A simple method that could easily be adopted for short-cycle crops that would allow the use of water-soluble nutrient sources yet curb nutrient losses is the use of substrates that retain targeted nutrients [3,24,25]. Substrates commonly used in the greenhouse and nursery industries often contain components with high cation exchange capacities (CEC) such as peat (or other organic derivatives) or mineral aggregates to increase water and nutrient retention [12,26–28]. High-CEC characterization of a substrate component does not always confer high anion exchange—meaning essential anionic macro- and micro-nutrients including P, S, B, and Mn may not be as readily adsorbed. This has led to reports of high P leaching in many horticultural crops growing in porous, soil-less substrates, even though $\text{HP}_2\text{O}_5^{-2}$ and $\text{H}_2\text{P}_2\text{O}_5^{-}$ have a high affinity for positively charged sites on soil and organic particles [29,30].

Activated aluminum (AA), a white, hardened granular substance, formed through the dehydroxylation of aluminum hydroxide, is commonly utilized in water filtration [31–33] for the removal of arsenic and fluorine in potable water and may serve as a potential substrate amendment that could increase anionic nutrient retention [34]. Activated aluminum has a high porosity, surface area, and anion affinity, and is relatively inexpensive due to its use in many products across various industries [35–38]. To date, AA has been utilized in the horticultural industry as a slow-release P fertilizer, and a patented process was developed in which AA is impregnated with P to provide a more controlled release mechanism to support plant growth [39,40].

The use of Al-based products draws immediate concern by those in the horticultural industry, given the phytotoxic effects of high concentrations of Al on plant growth with commonly displayed symptoms of severe root decline and nutrient deficiencies [41–45]. Aluminum comprises approximately 8% of the earth's crust, typically existing in soils as Al-oxides and aluminosilicate minerals that are influenced by soil properties including pH, cation exchange capacity, and organic matter content [44]. Toxic Al concentrations in highly weathered clay soils in humid regions of the United States require routine pH management to provide suitable growing conditions [46,47]. Similarly, substrate pH is adjusted through lime incorporation to counter the acidifying effects of peat or pine bark for containerized plants [48–52]. In contrast to soil aluminum, AA is a processed, comparatively stable substance between pH 4 and 10 [53], a range that spans the recommended pH of substrates primarily used for most containerized horticultural species [48], and would not be expected to have deleterious effects on *Tagetes patula*, a model short-cycle container crop.

The benefit of AA is that it would increase substrate anion nutrient retention to reduce anion leaching and enhance plant growth. This would mitigate the environmental risks associated with fertigation without necessitating any modification to standard fertigation practices. Therefore, the objective of this research is to evaluate the efficacy of AA as a substrate amendment to reduce anion nutrient losses without deleteriously affecting plant growth during the production of short-cycle ornamental species.

2. Materials and Methods

2.1. Study Design

A study was conducted on French marigolds (*Tagetes patula*) growing under greenhouse conditions for 28 days. Experiments were initiated between June 2020 (Exp1) and August 2022 (Exp2) at the Hill Farm teaching greenhouse on the Louisiana State University Campus located in Baton Rouge, LA, USA (30.41384 N, −91.17087 W). Sixteen marigolds grown in six-cell trays were selected for uniform height and quality and were then transplanted into PVC containers (10 cm diameter and 20 cm depth). All containers were filled with 1.07 kg of a pine bark-based substrate that consisted of a 6:1:1 ratio of pine bark/peat

moss/sand. Dry weight pine bark particles comprised 4.1% >6.3 mm, 11.4% 2 to 6.3 mm, 12.8% 0.7 to 2 mm, and 71.7% <0.7 mm. Particle size was determined by passing three oven-dried 100 g replicates through a column of sieves, agitating and shaking for five minutes using a Ro-Tap sieve shaker (W.S. Tyler, Mentor, OH, USA), after which particles remaining on each sieve were weighed to calculate percentages. The substrate had a container capacity, total porosity, and bulk density of $0.55 \pm 0.024 \text{ cm}^3 \text{ cm}^{-3}$, $0.7 \pm 0.001 \text{ cm}^3 \text{ cm}^{-3}$, and $0.46 \pm 0.002 \text{ g cm}^{-3}$, respectively, and a pH 5.97 and 0.31 dS m^{-1} electrical conductivity (EC). The substrate was amended with a micronutrient mix (Micromax Micronutrients, Burton, Ohio, USA) at 0.6 kg.m^{-3} , dolomitic lime (MK Minerals, Inc., Wathena, KS, USA) at 4.8 kg.m^{-3} , and treatments of AA (Riverland Industries, Baton Rouge, LA, USA) at 0, 20, 40, or 60 g per container.

Marigolds were fertigated daily with 200 ppm N, 88 ppm P, and 166 ppm K using a water-soluble fertilizer (20-20-20; Fertilome, VPG, Bonham, Texas) to reach container capacity. Changes in daily container capacity were measured gravimetrically for all control plants with average water losses calculated.

2.2. Plant Growth Measurements

Marigold growth index and plant quality were measured every seven days after planting (weeks after planting; WAP). Marigold growth index was calculated using the following plant growth index formula [54]:

$$\text{Plant Growth Index} = \frac{\text{height} + \left(\frac{\text{width1} + \text{width2}}{2}\right)}{2}$$

Marigold quality measurements were performed based on visual appearance on a scale of 1 to 9, with 1 representing poor plant size and color, and 9 representing ideal plant size and color. Shoot tissue was excised at the plant soil surface interface at 4 WAP. Shoots were dried at $40 \text{ }^\circ\text{C}$ ($104 \text{ }^\circ\text{F}$) for 72 h before biomass was determined gravimetrically.

2.3. Leachate Collection and Analyses

Containers were fitted with end caps with a single drainage hole. Containers were placed into a wooden frame so that leachate could be captured beneath each container into glass jars. Leachate was induced through the addition of 300 mL H_2O every WAP for four weeks. Leachate volume was measured with 25 mL subsamples collected and submitted to the Louisiana State University Soil Testing and Plant Analysis Laboratory (Louisiana State University, Baton Rouge, LA, USA) for quantitation of dissolved elements including P, S, Mn, Al, and B using inductively coupled plasma (ICP) optical emission spectroscopy (ICP SPECTRO ACRCOS Model FH E12, Kleve, Germany). Leachate samples were also measured for pH and EC (model HI-9813-6, Hanna Instruments, Smithfield, RI, USA) only in the second experiment.

2.4. Statistical Analysis

Two-way repeated measures of ANOVA were performed to determine whether there is a significant interaction between treatment and time on each variable. Linear fixed effect for repeated measurement models were conducted using the function `aov` from package `stats` in R (R Core Team, 2020, Vienna, Austria). Significant models were further analyzed by performing pairwise comparisons with Tukey's adjustment between treatments with an outcome at $\alpha = 0.05$. Marigold growth index, plant quality, and metal mass losses over time were graphed with standard errors applied to means.

Cumulative values for each variable were also analyzed to evaluate if treatments were significantly different. The experiment was determined as a random effect. Models were fitted using `lmer` from the package `lme4` also in R. *p*-values were considered significant at $\alpha = 0.05$ and comparisons were made with Tukey's adjustments.

3. Results

3.1. Marigold Growth and Quality

All marigolds grew rapidly in the first three weeks after planting with no differences among the AA-amended substrate treatments and controls (Figure 1).

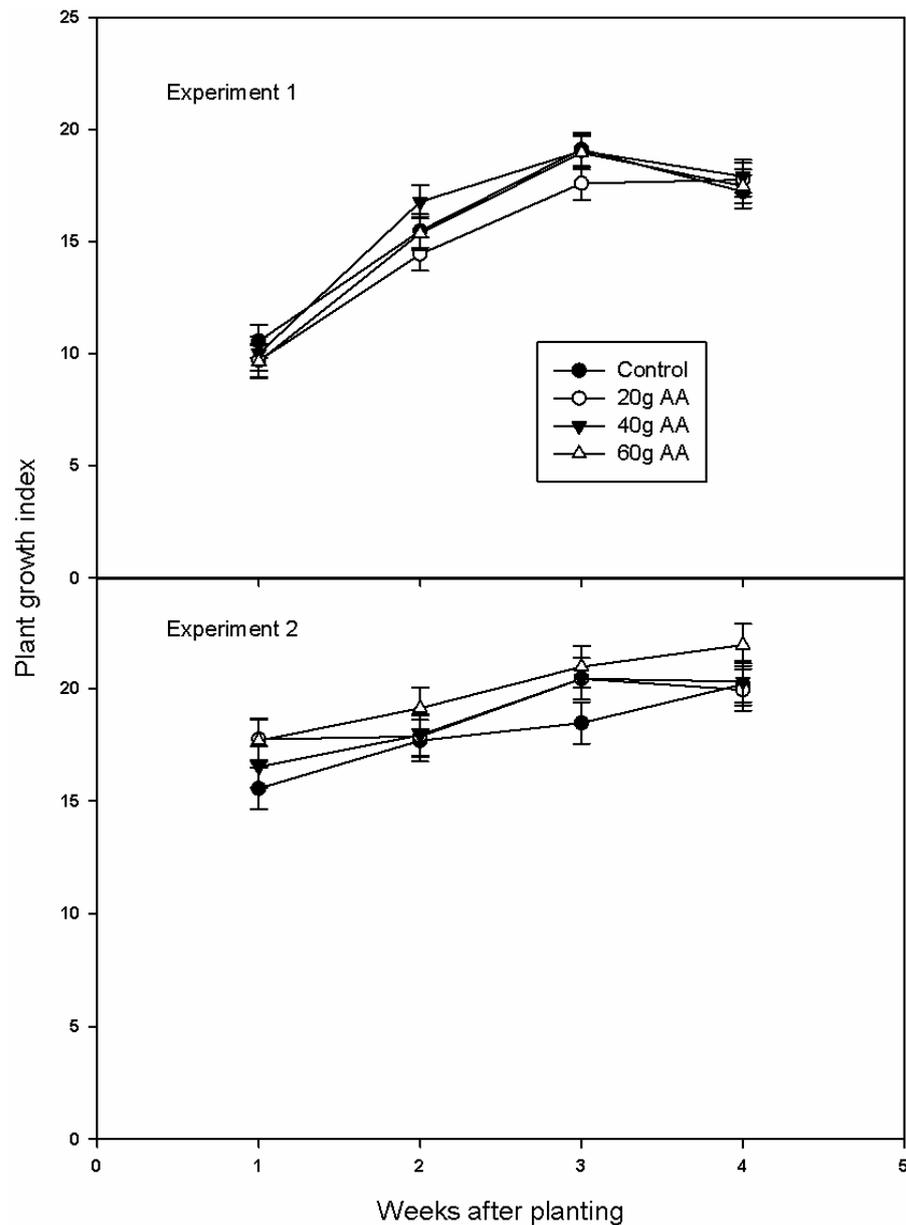


Figure 1. Growth index of *Tagetes* in substrates blended with various proportions of activated aluminum (AA).

At the conclusion of the experimental runs, the marigolds achieved growth indices ranging from 17.2 to 21.9 cm. The final plant quality ratings indicated that a similar caliber of plant quality was produced across all substrate types. The increasing amounts of AA amended within the substrate appeared to have no deleterious effect on marigold growth and quality during the four-week production cycle. Although the flowering ratings were not recorded, there was no observed effect of AA on marigold flowering.

3.2. Aluminum Leached

There were no consistent patterns in weekly (Figure 2) or cumulative leaching losses of Al (Table 1) between all treatments.

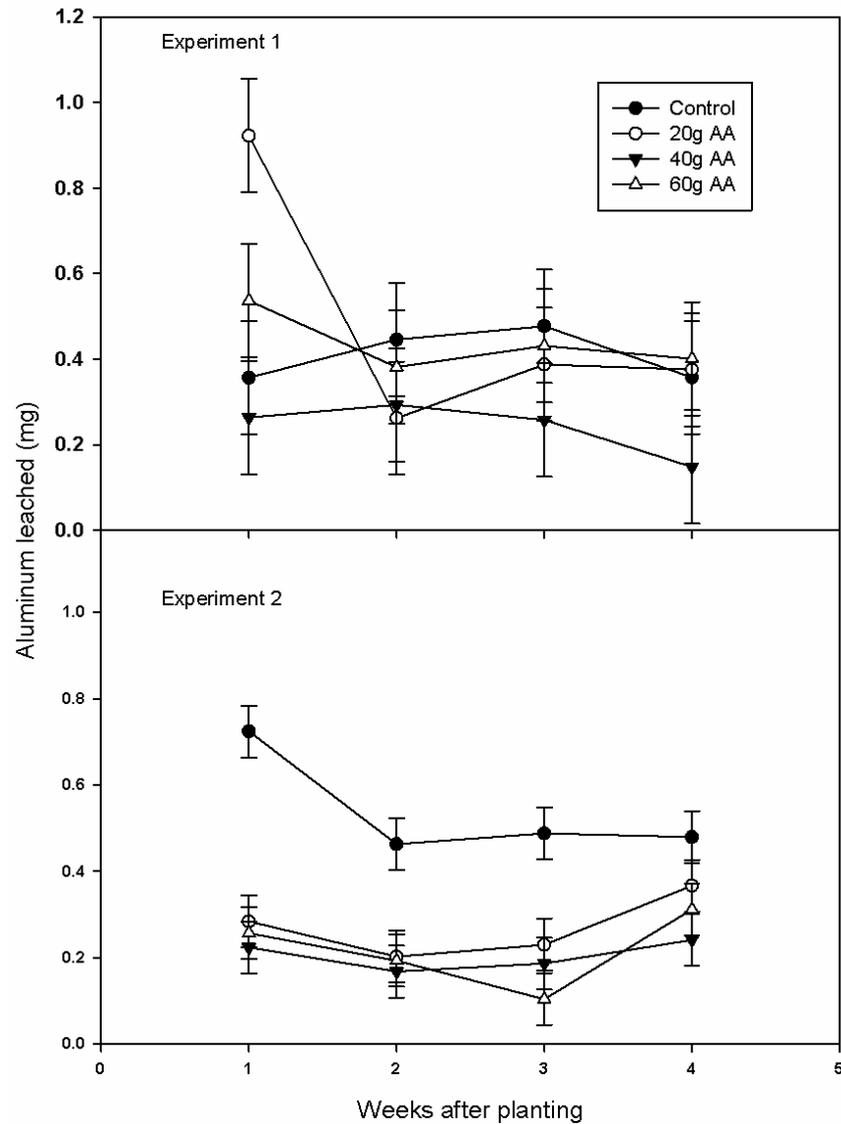


Figure 2. Weekly mass of aluminum leached from substrates blended with various proportions of activated aluminum (AA) over the course of two experiments.

Table 1. Average total mass of elements collected in leachate from substrates amended with various proportions of activated aluminum (AA) over the course of two experiments. Differences between treatment means, when significant, are represented by different letters.

Average Cumulative Mass Collected in Leachate (mg)				
	0 g AA	20 g AA	40 g AA	60 g AA
Aluminum	1.90 (a)	1.52 (a)	1.31 (ab)	0.89 (b)
Phosphorus	78.9 (a)	21.6 (b)	8.53 (b)	5.78 (b)
Boron	0.63 (a)	0.34 (b)	0.18 (c)	0.17 (c)
Manganese	3.96 (a)	0.54 (b)	0.11 (b)	0.11 (b)
Sulfur	107 (a)	42.0 (b)	8.02 (c)	4.32 (c)

The mass of the aluminum in the container leachate averaged below 1 mg for the control and all AA treatments on all sample days during both studies. There were no differences in the mass of aluminum leached from any of the AA treatments on any individual sample date; however, the control had more aluminum leaching in one WAP during experiment two. The cumulative mass of Al leached was similar among the AA treatments and controls, save for the 60 g of AA treatment leaching less total aluminum than the control. The cumulative mass of Al leached was between 0.8 and 2.2 mg for all treatments and experimental runs.

3.3. Nutrient and Leaching Losses

Increasing the AA mass from 20 to 60 g resulted in greater substrate nutrient retention to reduce cumulative P, S, B, and Mn leaching losses (Table 1). For example, amending the substrates with 20 g of AA reduced cumulative P losses between 69 and 87 percent of the control (POC) compared to 92 to 96 POC for 60 g of AA. A similar pattern measured for the cumulative P leaching losses also occurred for the cumulative B, Mn, and S leaching losses as the AA increased from 20 to 60 g within the container substrates. It is worth noting that tripling the mass of AA from 20 to 60 g did not necessarily lead to corresponding reductions in anionic nutrients leached, but that the reduction in losses were higher and more consistent at 60 g of AA. The greatest gradient change in nutrient retention occurred when the AA mass increased from 20 to 40 g. Amending a substrate with 40 g of AA led to higher and more consistent reductions for S, B, and Mn in both experimental runs, as well as P in the first experimental run, compared to 20 g of AA. In experiment one, the total amount of P lost in leachate was reduced by 69, 88, and 92% compared to the control for the substrates with 20, 40, and 60 g of AA, respectively. In experiment two, the amount of cumulative P that was lost in leachate was reduced by 87, 92, and 96% compared to the control for substrates with 20, 40, and 60 g of AA, respectively.

Accounting the cumulative losses of nutrients does characterize AA's nutrient retention properties as an amendment throughout the 4-week production cycle. However, the patterns of the nutrients leached over the production cycle provides insight into the retentive properties of AA with regard to the AA amendments (Figures 3 and 4).

The patterns for S, B, and Mn losses followed the typical leaching loss curves illustrated in past research examining substrate-incorporated nutrients prior to planting with no subsequent fertilizer additions. The nutrient leaching losses for S, B, and Mn were the highest in the initial WAP followed by declining losses over time, with the controls exhibiting the highest losses followed by decreasing masses of AA. The incorporation of AA at 40 and 60 g exhibited similar loss patterns with higher reductions in the initial nutrient leaching losses occurring in the first two WAP compared to the controls and the 20 g of AA treatment. Increasing the nutrient retention with 40 and 60 g of AA led to a reduced cumulative nutrient loading compared to 20 g of AA and controls.

Unlike S, B, and Mn, the P leaching losses increased substantially over the first three WAP for the controls, whereas all the AA treatments resulted in a higher P retention in the initial two WAP before exhibiting increasing P leaching losses. Decreasing the mass of AA from ≥ 40 g of AA to 20 g of AA resulted in increasing P leaching losses at three and four WAP, albeit all the AA treatments were significantly lower than the controls. Amending the substrate with 40 or 60 g of AA resulted in the most consistent reductions in P leached for the 4-week production cycle.

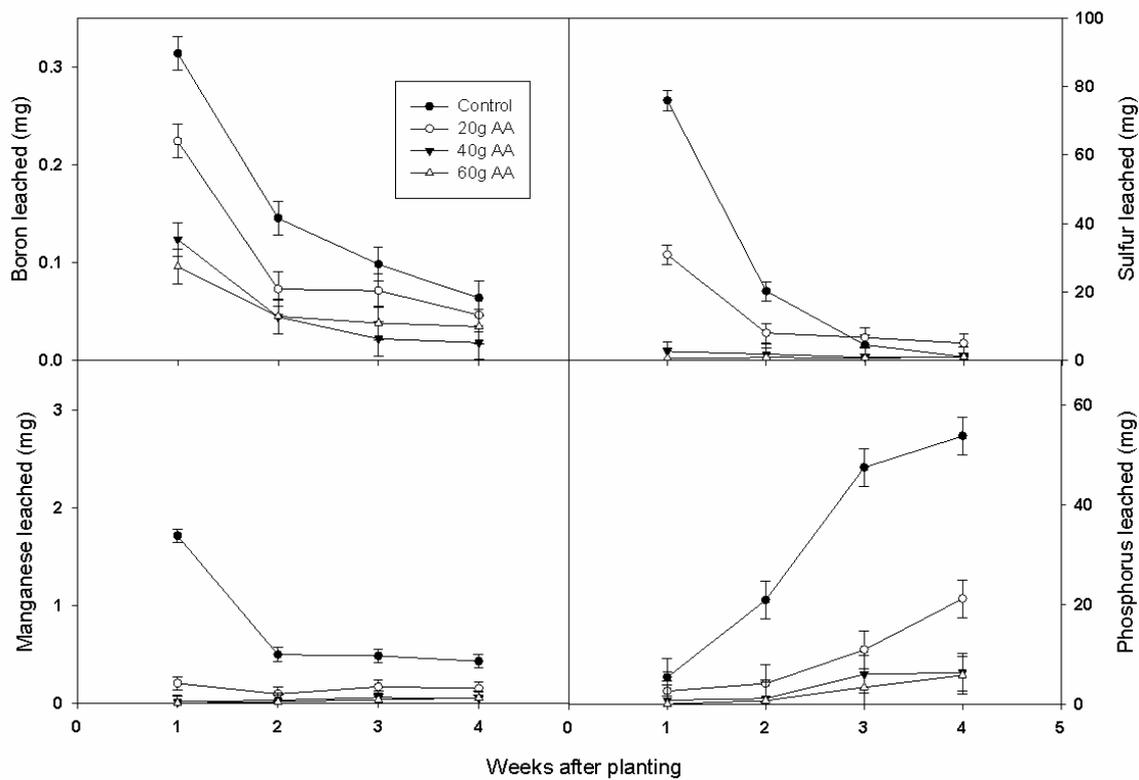


Figure 3. Mass of nutrients collected in leachate from substrates amended with various proportions of activated aluminum (AA) over the course of experiment one.

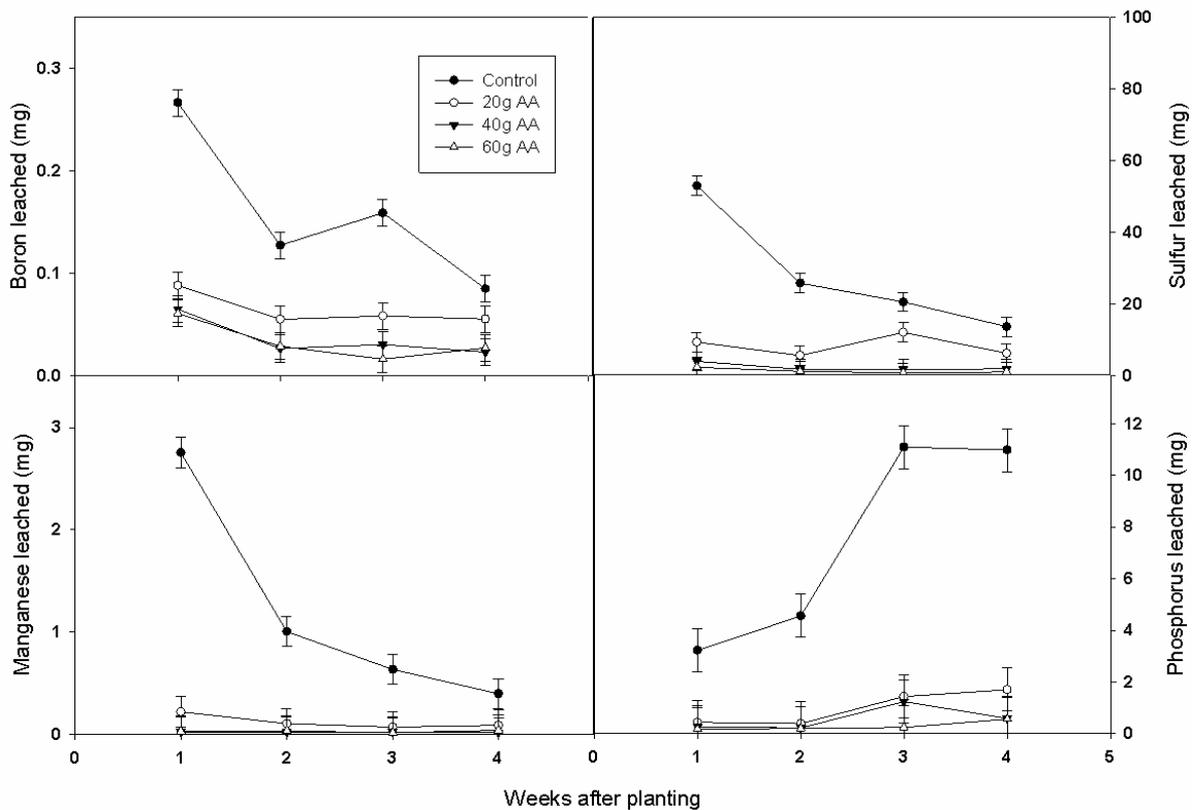


Figure 4. Mass of nutrients collected in leachate from substrates amended with various proportions of activated aluminum (AA) over the course of experiment two.

The incorporation of AA not only affected the pattern of nutrient loss over the 4-week production cycle but also the magnitude of nutrients lost between experimental runs for S, B, and Mn compared to P. The magnitude of S, B, and Mn leached between experimental runs was similar as illustrated in Figures 3 and 4, with the exception of the macronutrient S at high losses of 75.9, 30.9, 2.7, and 0.6 mg one WAP for the control, 20, 40, and 60 g of AA, respectively, in the first experimental run, compared to 52.9, 9.4, 4.0, and 2.3 mg in the second experimental run. In the case of P, this resulted in a pattern of increasing P losses weekly, but the magnitudes of the highest P lost were 127.9 and 29.9 mg total after four WAP for the first and second experimental runs, respectively.

All containers received the same daily volume of irrigation based on the average evapotranspiration of the sand-only controls per experimental run. However, evapotranspiration greatly differed between the two experimental runs with 4539 mL versus 1978 mL of fertigation volume applied containing 399.4 mg P versus 174.2 mg P, respectively, between the first and second experimental runs. The electrical conductivity (EC) was measured throughout the duration of the second experiment (Figure 5), providing a non-ion-specific assessment of the nutrient movement in the container leachate.

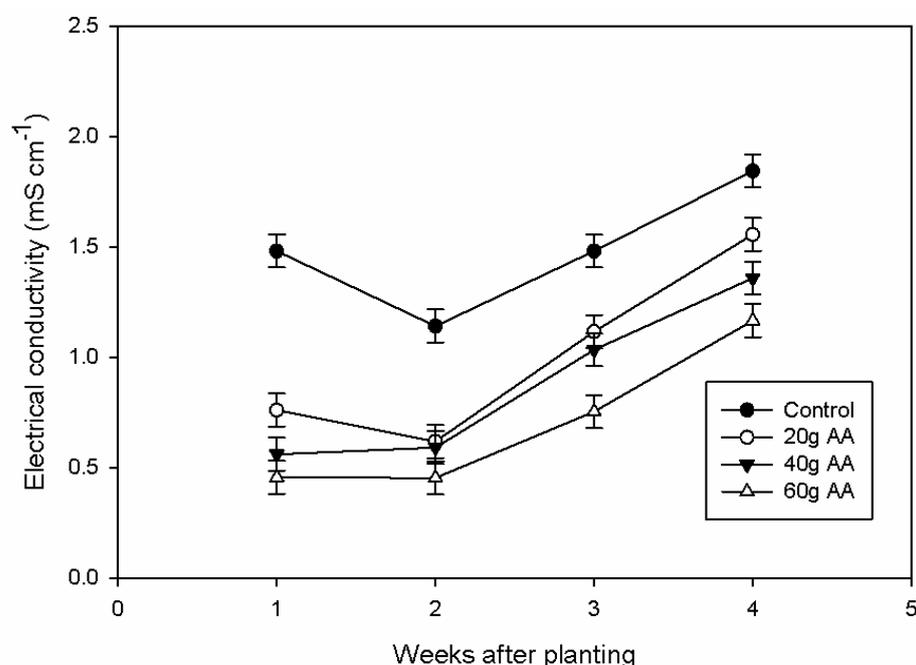


Figure 5. Electrical conductivity in leachate from substrates amended with various proportions of activated aluminum (AA) over the course of experiment two.

The control maintained a container leachate EC of >1.1 mS cm⁻¹ throughout the entire study and was greater than the substrates amended with 40 and 60 g of AA, respectively, on each individual sample date. The EC in the container leachate increased over time within each substrate; however, the most pronounced effects were observed in the first two WAP, where the leachate EC from all AA-amended substrates was below 0.8 mS cm⁻¹. The leachate pH was similarly measured throughout the second experiment, with all substrates maintaining an acidic pH over the first three WAP (control: 3.76; 20 g of AA: 4.92; 40 g of AA: 4.56; 60 g of AA: 4.6); however, all three AA-amended substrates had a pH that was neutral to slightly alkaline on the fourth and final WAP (20 g of AA: 7.03; 40 g of AA: 7.33; 60 g of AA: 7.48) compared to the mild decrease in acidity observed in the control (pH of 5.78).

4. Discussion

The production of short-cycle horticultural crops demands readily available provisions of fertilizer, rendering the application of water-soluble fertilizers via fertigation an oftentimes necessary component in the process [55,56]. A critical concern regarding the practice of fertigation is balancing the crop nutritional needs with the risk of nutrient loss to the environment, particularly with the deleterious impacts of eutrophication occurring globally. While both N and P are culpable in this phenomenon, it is indeed P that is often the more bioactive element, particularly in freshwater ecosystems [57]. As a management practice, nutrients are often overapplied to ensure that plant growth is unrestricted [2]. Reducing the amount of P applied via fertigation can lessen the downstream environmental risk; however, this may be impractical as the wide array of commonly produced ornamental taxa have different P requirements needed to achieve peak productivity, morphological form, and photosynthetic performance [58]. Therefore, this study investigated amending substrates with Al compounds to adsorb and retain P within a container, thus mitigating the environmental risks presented by excessive P loss to the environment without neglecting crop P requirements.

The substrates amended with AA demonstrated a substantial capacity to reduce leached P. Phosphorus is subject to AA-sorption mechanisms such as surface complexation and surface precipitation under different pH and P loading conditions, severely restricting the mobility and bioavailability of this element [59–61]. This manifested in the increases over time in effluent P in leachate from the control substrate juxtaposed with the comparatively stable masses of effluent P from the AA-enhanced substrates. This indicates that increasing amounts of Al in a substrate provides enhanced buffering capacity for P flux, as more sites are available for P adsorption. While increasing the amount of AA in a substrate created a more muted, stable mass of P in container leachate over time, the incorporation of 20 g of AA was typically as successful as the higher AA rates in accomplishing this purpose.

The incorporation of AA into substrates was not met with a concomitant increase in Al mass in container leachate. In fact, the unamended substrate had a greater leachate mass of Al on the first sample date of Exp2, compared to all AA-enhanced substrates. Overall, the Al from container leachate in this study were similar to the extent that they all maintained relative stability and seldom exceeded 0.5 mg. The concentration of Al present in a substrate/soil bears both positive and negative implications toward plant health [62,63], and given the similarity in the leachate Al content and the quality of plants produced, the addition of AA to the substrate did not present negative implications.

The capacity for AA-enhanced substrates to buffer other elements of interest was also observed with regard to B, Mn, and S. The mass of all three of these elements in the leachate from the unamended containers exhibited a dramatic decline from the first sample date to the second sample date, prior to plateauing for the duration of the study. Conversely, the AA-enhanced substrates maintained a stable, lower mass of all three elements in the container leachate throughout the duration of Exp1 and Exp2, with increasing amounts of AA leading to slightly more reduction. This suggests that the incorporation of AA binds and retains these necessary anionic micro-nutrients in situ more effectively than the unamended substrates. A more holistic interpretation of nutrient loss in container leachate was provided by the EC analysis, where the addition of AA led to dramatic reductions in EC one and two WAP, providing an initial buffer to early nutrient loss. While these differences became more muted as time elapsed, the mitigation of nutrient loss early in the production cycle is especially valuable in short-cycle crops. The universal increase in leachate pH for all substrates between three and four WAP could possibly be explained by the cumulative additions of nutrients (both macro and micro) building up a buffering capacity in situ, where it is possible that complexes involving sorbed P and Mg may have precipitated with source water alkalinity.

The implementation and adoption of AA-enhanced substrates as a method to reduce P loss to the environment demands evidence that this practice does not come at the expense of crop quality. The two metrics employed in the assessment of *Tagetes* throughout this

study encompassed quantitative and qualitative, objective and subjective measurements. The growth index provides insight into the overall volume of a plant, where both rounds of experiments yielded plants of equivalent final size for all treatments. The growth index was equivalent on each individual sample date throughout the duration of each experiment, thus demonstrating the consistency in the growth rate dynamics maintained over time. The results were consistent with the observations made by Amaizah et al. [64] in a study measuring the growth of mustard (*Sinapis alba*) in soils blended with and without recycled Al-P. In that study, an equivalent fresh and dry biomass was achieved when using Al-P compared to typical superphosphate or rock phosphate treatments; furthermore, there were reductions in both the soil and plant Al content when using recycled Al-P. The subjective assessments of the quality of the *Tagetes* replicates identified no differences in the plant aesthetics on any individual sample date or at the termination of the experiments.

5. Conclusions

The results presented in this study demonstrate that the incorporation of AA as a substrate component in horticultural crop production is an effective tool in retaining P and other critical anionic micronutrients within a substrate. Short-term crops which may rely on fertigation to achieve immediate nutrient availability can be effectively produced to the same quality standards while mitigating the environmental risks posed via this practice. Incorporating AA, even in relatively low amounts, is sufficient to achieve these goals in short-cycle crops; however, it is necessary to consider the crop size and cycle duration when selecting the incorporation rate of Al, as it is indeed likely that larger plants and longer crop cycles may lead to sorption site saturation and reduced P removal efficiency. Furthermore, the retention of P within container substrates may allow the modification of prescribed fertigation rates at crucial times in the crop production cycle, as it is possible that retained, sorbed P may be bioavailable for plant uptake and additional P applications would be rendered unnecessary. Continued research involving substrate/AA physical/hydraulic engineering, variable P application rates, and crop-specific studies can provide further insight and incentivize the implementation of this environmentally sustainable production practice.

Author Contributions: Conceptualization, J.B. (Jeffrey Beasley); methodology, J.B. (Jennifer Blanchard), L.B. and J.B. (Jeffrey Beasley); validation, J.B. (Jeffrey Beasley) and L.S.; formal analysis, L.S.; investigation, J.B. (Jennifer Blanchard) and L.B.; resources, J.B. (Jeffrey Beasley); data curation, J.B. (Jennifer Blanchard) and D.E.A.; writing—original draft preparation, D.E.A.; writing—review and editing, J.S.F. and J.B. (Jeffrey Beasley); visualization, D.E.A.; project administration, J.B. (Jeffrey Beasley). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the USDA-NIFA Hatch Project 1025897.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data for this research are available upon request.

Acknowledgments: We would like to acknowledge John Novak for his technical assistance regarding activated aluminum properties and Riverland Industries located in Baton Rouge, LA for supplying the activated aluminum used in the study.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Krofft, C.E.; Pickens, J.M.; Newby, A.F.; Sibley, J.L.; Fain, G.B. The effect of leaching fraction-based irrigation on fertilizer longevity and leachate nutrient content in a greenhouse environment. *Horticulturae* **2020**, *6*, 43. [[CrossRef](#)]
2. Jahromi, N.B.; Walker, F.; Fulcher, A.; Altland, J.; Wright, W.C. Growth response, mineral nutrition, and water utilization of container-grown woody ornamentals grown in biochar-amended pine bark. *HortScience* **2018**, *53*, 347–353. [[CrossRef](#)]

3. Owen, J.S., Jr.; Warren, S.L.; Bilderback, T.E.; Albano, J.P. Phosphorus rate, leaching fraction, and substrate influence on influent quantity, effluent nutrient content, and response of a containerized woody ornamental crop. *HortTechnology* **2008**, *43*, 906–912. [[CrossRef](#)]
4. Zhu, H.; Frants, J.M.; Derksen, R.C.; Krause, C.R. Investigation of drainage and plant growth from nursery container substrate. *Appl. Eng. Agric.* **2007**, *23*, 289–297. [[CrossRef](#)]
5. Zhu, H.; Zondag, R.H.; Merrick, J.; Demaline, T.; Krause, C.R. Nutrient leaching from container-grown ornamental tree production. *J. Environ. Hortic.* **2015**, *33*, 76–83. [[CrossRef](#)]
6. Abdi, D.E.; Owen, J.S., Jr.; Brindley, J.C.; Birnbaum, A.; Cregg, B.M.; Fernandez, R.T. Irrigation return flow and nutrient movement mitigation by irrigation method for container plant production. *Irrig. Sci.* **2021**, *5*, 567–585. [[CrossRef](#)]
7. Bilderback, T. Water management is key in reducing nutrient runoff from container nurseries. *HortTechnology* **2002**, *4*, 541–544. [[CrossRef](#)]
8. Tyler, H.H.; Warren, S.L.; Bilderback, T.E. Reduced leaching fractions improve irrigation use efficiency and nutrient efficacy. *J. Environ. Hortic.* **1996**, *14*, 199–204. [[CrossRef](#)]
9. Majsztrik, J.C.; Fernandez, R.T.; Fisher, P.R.; Hitchcock, D.R.; Lea-Cox, J.; Owen, J.S., Jr.; Oki, L.R.; White, S.A. Water use and treatment in container-grown specialty crop production: A review. *Water Air Soil Pollut.* **2017**, *228*, 151. [[CrossRef](#)]
10. Yazdi, M.N.; Sample, D.J.; Scott, D.; Owen, J.S.; Ketabchy, M.; Alamdari, N. Water quality characterization of storm and irrigation runoff from a container nursery. *J. Environ. Hortic.* **2019**, *667*, 166–178. [[CrossRef](#)] [[PubMed](#)]
11. Agro, E.; Zheng, Y. Controlled-release fertilizer application rates for container nursery crop production in Southwestern Ontario, Canada. *HortScience* **2014**, *11*, 1414–1423. [[CrossRef](#)]
12. Chen, J.; Huang, Y.; Caldwell, R.D. Best management practices for minimizing nitrate leaching from container-grown nurseries. *Sci. World* **2001**, *1*, 96–102. [[CrossRef](#)]
13. Garber, M.P.; Ruter, J.M.; Midcap, J.T.; Bondari, L. Survey of container nursery irrigation practices in Georgia. *HortTechnology* **2002**, *12*, 727–731. [[CrossRef](#)]
14. Yeager, T.; Wright, R.; Fare, D.; Gilliam, C.; Johnson, J.; Bilderback, T.; Zondag, R. Six state survey of container nursery nitrate nitrogen runoff. *J. Environ. Hortic.* **1993**, *11*, 206–208. [[CrossRef](#)]
15. Mangiafico, S.S.; Newman, J.; Merhaut, D.J.; Gan, J.; Faber, B.; Wu, L. Nutrients and pesticides in stormwater runoff and soil water in production nurseries and citrus and avocado groves in California. *HortTechnology* **2009**, *19*, 360–367. [[CrossRef](#)]
16. Rose, M.A.; Rose, M.; Wang, H. Fertilizer concentration and moisture tension affect growth and foliar N, P, and K contents of two woody ornamentals. *HortScience* **1999**, *34*, 246–250. [[CrossRef](#)]
17. Majsztrik, J.C.; Ristvey, A.G.; Ross, D.S.; Lea-Cox, J.D. Comparative water and nutrient application rates among ornamental operations in Maryland. *HortScience* **2018**, *53*, 1364–1371. [[CrossRef](#)]
18. Warsaw, A.L.; Fernandez, R.T.; Cregg, B.M.; Andresen, J.A. Container-grown ornamental plant growth and water runoff nutrient content and volume under four irrigation treatments. *HortScience* **2009**, *44*, 1573–1580. [[CrossRef](#)]
19. Mangiafico, S.S.; Gan, J.; Wu, L.; Lu, J.; Newman, J.P.; Faber, B.; Merhaut, D.J.; Evans, R. Detention and recycling basins for managing nutrient and pesticide runoff from nurseries. *HortScience* **2008**, *43*, 393–398. [[CrossRef](#)]
20. Lu, J.; Wu, L.; Newman, J.; Faber, B.; Gan, J. Degradation of pesticides in nursery recycling pond waters. *J. Agric. Food Chem.* **2006**, *54*, 2658–2663. [[CrossRef](#)]
21. Ristvey, A.G.; Belayneh, B.E.; Lea-Cox, J.D. A comparison of irrigation-water containment methods and management strategies between two ornamental production systems to minimize water security threats. *Water* **2019**, *11*, 2558. [[CrossRef](#)]
22. Spangler, J.T.; Sample, D.J.; Fox, L.J.; Owen, J.S., Jr.; White, S.A. Floating treatment wetland aided nutrient removal from agricultural runoff using two wetland species. *Ecol. Eng.* **2019**, *127*, 468–479. [[CrossRef](#)]
23. Sanders, K.R.; Beasley, J.S. Fertilizer source affects nutrient losses from hybrid bermudagrass during surface runoff. *HortTechnology* **2019**, *6*, 952–957. [[CrossRef](#)]
24. Broschat, T.K. Substrate nutrient retention and growth of container-grown plants in clinoptilolite zeolite-amended substrates. *HortTechnology* **2001**, *11*, 75–78. [[CrossRef](#)]
25. Owen, J.S., Jr.; Warren, S.L.; Bilderback, T.E.; Albano, J.P. Industrial mineral aggregate amendment affects physical and chemical properties of pine bark substrates. *HortScience* **2007**, *42*, 1287–1294. [[CrossRef](#)]
26. Altland, J.E.; Locke, J.C.; Krause, C.R. Influence of pine bark particle size and pH on cation exchange capacity. *HortTechnology* **2017**, *24*, 554–559. [[CrossRef](#)]
27. Fields, J.S.; Owen, J.S., Jr.; Altland, J.E.; van Iersel, M.W.; Jackson, B.E. Soilless substrate hydrology can be engineered to influence plant water status for an ornamental containerized crop grown within optimal water potentials. *J. Am. Soc. Hortic. Sci.* **2018**, *143*, 268–281. [[CrossRef](#)]
28. Shreckhise, J.H.; Owen, J.S., Jr.; Eick, M.J.; Niemera, A.X.; Altland, J.E.; White, S.A. Dolomite and micronutrient fertilizer affect phosphorus fate in pine bark substrate used for containerized nursery crop production. *Soil Sci. Soc. Am. J.* **2019**, *83*, 1410–1420. [[CrossRef](#)]
29. Godoy, A.; Cole, J.C. Phosphorus source affects phosphorus leaching and growth of containerized spiraea. *HortScience* **2000**, *35*, 1249–1252. [[CrossRef](#)]
30. Marconi, D.J.; Nelson, P.V. Leaching of applied phosphorus in container media. *Sci. Hortic.* **1984**, *22*, 275–285. [[CrossRef](#)]

31. Garelick, H.; Dybowska, A.; Valsami-Jones, E.; Priest, N.D. Remediation technologies for arsenic contaminated drinking waters. *J. Soils Sediments* **2005**, *5*, 182–190. [CrossRef]
32. Nicomel, N.R.; Leus, K.; Folens, K.; Van Der Voort, P.; Du Lang, G. Technologies for arsenic removal from water: Current status and future perspectives. *Int. J. Environ. Res. Public Health* **2015**, *13*, 62. [CrossRef] [PubMed]
33. Sorg, T.J.; Chen, A.S.C.; Wang, L.; Kolisz, R. Regenerating an arsenic removal iron-bed adsorptive media system, part 1: The regeneration process. *Am. Water Work. Assoc.* **2017**, *109*, 13–24. [CrossRef]
34. Su, T.; Guan, X.; Gu, G.; Wang, J. Adsorption characteristics of As(V), Se (IV), and V(V) onto activated alumina: Effects of pH, surface loading, and ionic strength. *J. Colloid Interface Sci.* **2008**, *326*, 347–353. [CrossRef]
35. Scott, I.S.P.C.; Penn, C.J.; Huang, C.H. Development of a regeneration technique for aluminum-rich and iron-rich phosphorus sorption materials. *Water* **2020**, *12*, 1784. [CrossRef]
36. Wang, J.; Zhang, Y.; Feng, C.; Li, J.; Li, G. Adsorption capacity for phosphorus comparison among activated alumina, silica sand and anthracite coal. *J. Water Resour. Prot.* **2009**, *4*, 260–264. [CrossRef]
37. Wu, G.; Liu, G.; Li, X.; Peng, Z.; Zhou, Q.; Qi, T. Enhanced phosphate removal with fine activated alumina synthesized from a sodium aluminate solution: Performance and mechanism. *RSC Adv.* **2022**, *12*, 4562–4571. [CrossRef]
38. Yu, C.; Liu, L.; Wang, X.; Fu, J.; Wu, Y.; Feng, C.; Wu, Y.; Shen, J. Fluoride removal performance of highly porous activated alumina. *Journal of sol-gel science and technology. J. Sol-Gel Sci. Technol.* **2023**, *106*, 471–479. [CrossRef]
39. International Publication Number WO02/083598A1. U.S. Patent No. 5,693,119. Available online: <https://patents.google.com/patent/WO2002083598A1/en> (accessed on 27 February 2023).
40. Patent Number 6287357. Available online: <https://patents.justia.com/patent/6287357> (accessed on 27 February 2023).
41. He, H.; Li, Y.; He, L.F. Aluminum toxicity and tolerance in Solanaceae plants. *S. Afr. J. Bot.* **2019**, *123*, 23–29. [CrossRef]
42. Panda, S.K.; Baluska, F.; Matsumoto, H. Aluminum stress signaling in plants. *Plant Signal. Behav.* **2009**, *4*, 592–597. [CrossRef]
43. Rahman, M.A.; Lee, S.H.; Hee, C.J.; Kabir, A.H.; Jones, C.S.; Lee, K.W. Importance of mineral nutrition for mitigating aluminum toxicity in plants on acidic soils: Current status and opportunities. *Int. J. Mol. Sci.* **2018**, *19*, 3073. [CrossRef] [PubMed]
44. Shetty, R.; Vidya, C.S.N.; Prakash, N.B.; Lux, A.; Vaculik, M. Aluminum toxicity in plants and its possible mitigation in acid soils by biochar: A review. *Sci. Total Environ.* **2021**, *765*, 142744. [CrossRef] [PubMed]
45. Zheng, S.J. Crop production on acidic soils: Overcoming aluminium toxicity and phosphorus deficiency. *Ann. Bot.* **2010**, *106*, 183–184. [CrossRef]
46. Gillespie, C.J.; Antonangelo, J.A.; Zhang, H. The response of soil pH and exchangeable Al to alum and lime amendments. *Agriculture* **2021**, *11*, 547. [CrossRef]
47. Silva, S. Aluminum toxicity targets in plants. *J. Bot.* **2012**, *2012*, 219462. [CrossRef]
48. Altland, J.E. Lime rate affects substrate pH and container-grown birch trees. *Comm. Soil Sci. Plant Anal.* **2019**, *50*, 93–101. [CrossRef]
49. Huang, J.; Fisher, P.R.; Argo, W.R. Container substrate-pH response to differing limestone type and particle size. *HortScience* **2007**, *42*, 1268–1273. [CrossRef]
50. Jackson, B.E.; Wright, R.D.; Gruda, N. Container medium pH in a pine tree substrate amended with peatmoss and dolomitic limestone affects plant growth. *HortScience* **2009**, *44*, 1983–1987. [CrossRef]
51. Owen, W.G.; Jackson, B.E.; Fonteno, W.C.; Whipker, B.E. Liming requirements of greenhouse peat based substrates amended with pine wood chips as a perlite alternative. *HortTechnology* **2020**, *30*, 219–230. [CrossRef]
52. Taylor, M.D.; Kreis, R.; Reito, L. Establishing growing substrate pH with compost and limestone and the impact on pH buffering capacity. *HortScience* **2016**, *51*, 1153–1158. [CrossRef]
53. Wefers, K.; Misra, C. *Oxides and Hydroxides of Aluminum*; Alcoa Laboratories Technical Paper No. 19; Alcoa Research Laboratories: Pittsburgh, PA, USA, 1987.
54. Irmak, S.; Haman, D.Z.; Irmak, A.; Jones, J.W.; Campbell, K.L.; Crisman, T.L. Measurement and analyses of growth and stress parameters of *Viburnum odoratissimum* (Ker-gawl) grown in a multi-pot box system. *HortScience* **2004**, *39*, 1445–1455. [CrossRef]
55. García-Gaytán, V.; Hernández-Mendoza, F.; Coria-Téllez, A.V.; García-Morales, S.; Sánchez-Rodríguez, E.; Rojas-Abarca, L.; Daneshvar, H. Fertigation: Nutrition, stimulation and bioprotection of the root in high performance. *Plants* **2018**, *7*, 88. [CrossRef] [PubMed]
56. Malhotra, S.K. Water soluble fertilizers in horticultural crops—An appraisal. *Indian J. Agric. Sci.* **2016**, *86*, 1245–1256.
57. Correll, D.L. The role of phosphorus in the eutrophication of receiving waters: A review. *J. Environ. Qual.* **1998**, *27*, 261–266. [CrossRef]
58. Poudyal, S.; Owen, J.S., Jr.; Sharkey, T.D.; Fernandez, R.T.; Cregg, B. Phosphorus requirement for biomass accumulation is higher compared to photosynthetic biochemistry for three ornamental shrubs. *Sci. Hortic.* **2021**, *275*, 109719. [CrossRef]
59. Massey, M.S.; Zohar, I.; Ippolito, J.A.; Litaor, M.I. Phosphorus sorption to aluminum-based water treatment residuals reacted with dairy wastewater: 2. X-Ray Absorption Spectroscopy. *J. Environ. Qual.* **2018**, *47*, 546–553. [CrossRef]
60. Tanada, S.; Kabayama, M.; Kawasaki, N.; Sakiyama, T.; Nakamura, T.; Araki, M.; Tamura, T. Removal of phosphate by aluminum oxide hydroxide. *J. Colloid Interface Sci.* **2003**, *257*, 135–140. [CrossRef] [PubMed]
61. Wang, X.; Phillips, B.L.; Boily, J.F.; Hu, Y.; Hu, Z.; Yang, P.; Feng, X.; Xu, W.; Zhu, M. Phosphate sorption speciation and precipitation mechanisms on amorphous aluminum hydroxide. *Soil Syst.* **2019**, *3*, 20. [CrossRef]
62. Bojórquez-Quintal, E.; Escalante-Magaña, C.; Echevarría-Machado, I.; Martínez-Estévez, M. Aluminum, a friend or foe of higher plants in acid soils. *Front. Plant Sci.* **2017**, *8*, 1767. [CrossRef]

63. Brunner, I.; Sperisen, C. Aluminum exclusion and aluminum tolerance in woody plants. *Front. Plant Sci.* **2013**, *4*, 172. [[CrossRef](#)]
64. Amaizah, N.R.; Cakmak, D.; Saljnikov, S.; Roglic, G.; Kokovic, N.; Manoilovic, D. Effect of waste Al-phosphate on soil and plant. *Plant Soil Environ.* **2013**, *59*, 130–135. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.