Evaluation of synthetic hydroxyapatite as a potential phosphorus fertilizer for application in Forest plantations

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ABSTRACT

Synthetic hydroxyapatite (HA) was compared against triple superphosphate (TSP) and two unprocessed phosphate rocks (PR1, PR2) to (1) quantify and assess a synthetic lamellar structured-HA as a phosphorus early rotation fertilizer for \textit{Eucalyptus} saplings. Soil incubation experiments verified that HA released more diffusive phosphorus into the soil than non-synthetic phosphate rock and had similar amounts of diffusive phosphorus as TSP. The solubility of HA at pH 3 and pH 6 was higher than that of raw ground phosphate rocks (apatites). Total dry-matter yield (DMY) and shoot-length of \textit{Eucalyptus} seedlings grown for 154 days in acid soil (pH 4.9) were increased significantly by the application of HA compared to the control, PR2, and mixed (HA + PR2). The lack of a DMY response using TSP indicates that phosphorus may not have been the limiting factor. However, considering TSP and HA had similar solubilities and released diffusive phosphorus at similar levels, the only variable we failed to control for was the CaCO\textsubscript{3} provided by the HA and not the TSP. Further experimentation is needed to confirm this hypothesis. Overall, HA is a promising candidate to supplement traditional phosphorus fertilizers for acidic sandy \textit{Eucalyptus} silviculture.

Introduction

Phosphorus (P) fertilization is a commonly used management practice in forest plantations worldwide to maximize forest productivity (Albaugh et al. 2019). Various methods and techniques are implemented to optimize phosphorus use efficiency in forest systems, such as erosion control, fertilization, and improved genetics. This optimization is a requirement due to increasing prices and scarcity of finite phosphorus mineral deposits where 90% of our water-soluble phosphorus fertilizers are still mined from (Jasinski 2017). Phosphate rocks, particularly apatites (Ca\textsubscript{5}(PO\textsubscript{4})\textsubscript{3}(OH, F)), are the base ingredient and unprocessed, can be used as a cheaper alternative to their processed water-soluble end products. Unprocessed and ground apatites have been successfully utilized as slow-release P fertilizers in various cropping systems (Dahanayake et al. 1995; Aarnio et al. 2003; Zapata and Roy 2004). The main disadvantages associated with using phosphate rocks as fertilizer relates to the low reactivity and soil availability compared to water-soluble fertilizers (Liu and Lai 2014). The low reactivity of these apatites can be disadvantageous depending on the crop being fertilized. For instance, annual crops may see little benefit from these slow-release apatites, but trees, e.g. \textit{Pinus} and \textit{Eucalyptus} sp., have been fertilized to great success with slow-release apatites (Aarnio et al. 2003; Bassaco et al. 2018). Unfortunately, as with any unprocessed and mined material, the variability and quality of mined apatites are subject to change depending on the natural origin and source of the product (Dahanayake et al. 1995; Kinnunen et al. 2003). These variations and the debate on phosphorus security make finding highly reactive phosphate rock sources for which the agronomic potential and economic feasibility are limited (Cordell and White 2011).

A proposed solution to many of these uncertainties is a recently proposed novel class of P-containing synthetic hydroxyapatites (Liu and Lai 2014; Montalvo et al. 2015; Kleinman et al. 2002; Taşkin et al. 2018; Xiong et al. 2018; Marchiol et al. 2019). Unlike mined phosphate rock fertilizers, this fertilizer class does not have to be extracted from the ground. Instead, it is synthesized by reacting a calcium carbonate-containing mineral precursor and orthophosphoric acid, giving it unique properties, including higher surface areas and higher reactivity in soil (Clark and Turner 1955; Minh et al. 2014; Gypser and Freese 2020). The efficacy of...
synthetic HA is attributed to the high solubility and increased reactivity attributed to their high specific surface area. However, the results from different studies on solubility, soil-and bioavailability, and the agronomic effectiveness of these HA products are inconsistent and often contradictory. For example, Liu and Lal (2014) demonstrated that synthetic HA was more effective than water-soluble P sources in increasing soybean plant growth rate and seed yield. Contrarily, Montalvo et al. (2015) reported no significant difference in wheat growth between synthetic HA and Triple-super Phosphate (TSP) treatments in Andisols whereas the dry-matter yield using synthetic HA was less than TSP in Oxisols. In Andisols, the dry-matter yield of wheat with HA in the nano range (particle size 22 nm) was significantly higher than that with bulk-HA (particle 600 nm), presumably due to the increased dissolution rate of HA particles with decreasing particle size.

The potential for the application of HA in high-intensity forest systems remains mainly unexplored (Bassaco et al. 2018; Albaugh et al. 2019). This study evaluates the potential application of a novel synthetic HA-containing mineral with a high surface area as starter phosphorus fertilizer in forestry. Unlike other forms of HA, the material referred to as HA in this study is, in fact, a synthesized mineral conglomerate that is present in the form of micronized calcium carbonate particles and lamellar structured hydroxyapatite on the particle surface, which are characterized by very high specific surface area. The mineral's increased surface area and porosity lead to various exciting properties for selected applications (Lundin et al. 2017; Ozyhar et al. 2021). This HA has not yet been assessed concerning its potential as a phosphorus fertilizer in forest systems. Due to its unique properties, i.e. expected high reactivity in combination with limited leaching potential, the application of synthetic lamellar structured HA is considered a promising alternative to water-soluble fertilizers. These properties make synthetic HA a potential starter fertilizer that could be applied directly to the seedling at the time of planting, providing a localized and fast supply of P close to the root system while minimizing the risk of leaching, run-off, and damage to the roots (Kleinman et al. 2002). The opportunity for localized application close to the root system is a significant advantage since it is hypothesized to have potential benefits for developing it (Marchiol et al. 2019).

Our hypotheses are H₁: Synthetic hydroxyapatite releases more diffusive phosphorus in acidic soil than non-synthetic phosphate rocks. H₂: Synthetic hydroxyapatite has a higher solubility than non-synthetic phosphate rocks. H₃: Synthetic hydroxyapatite will have a positive growth effect on Eucalyptus globulus seedlings under greenhouse conditions compared to non-synthetic phosphate rocks. To test these hypotheses, we divided our experiment into separate sections. TSP was used as a positive control to compare variables to a conventionally applied water-soluble fertilizer. A negative control using neither phosphorus fertilizer was our negative. To test H₁, a soil incubation study was performed to compare extractable and diffusive P levels released from all fertilizers. To examine H₂, HA fertilizer will be compared to non-synthetic phosphate rock, and TSP using two different pHs under laboratory conditions and verified using electron microscopy and chemical extraction. To test our final hypothesis, H₃, we will examine the effect of each fertilizer on Eucalyptus globulus seedlings' growth under greenhouse conditions. Eucalyptus was selected since it is one of the most commercially important forest species globally, often planted in acidic soils requiring P fertilization (Xu et al. 2005; Bassaco et al. 2018). Since many commercial forest plantations, especially in the tropics, are established on nutrient-poor and acidic soils, the focus of this study was to evaluate the HA’s performance in an acidic environment. Both soil incubation trial and growth response study performed in this study utilized nutrient-poor soil with high acidity (pH: 4.9).

Materials and methods

Sources of phosphorus products

Synthetic hydroxyapatite (HA)-containing was synthesized using a proprietary manufacturing process. The individual mineral particles are present in CaCO₃ and lamellar-structured HA on the particle surface (Figure 1(a)). The synthetic HA product composition consisted of 41% unreacted CaCO₃ and 59% of precipitated HA, Ca₁₀(PO₄)₆(OH)₂, as identified by X-ray diffraction (XRD). The weight median size (d₅₀) of the particles was in the micrometer range (6.6 µm), with the specific surface area of 53 m² g⁻¹ measured by the standard BET gas adsorption isotherm (Fagerlund 2010).

The other P fertilizers tested were two phosphate rocks (PR1 & PR2) taken from different sources and TSP. PR1 had 5.9% total P; the mineralogical composition was 47% apatite, 49% quartz, and no significant amount of CaCO₃. PR1 was collected from a small PR deposit in Poland followed by grinding to d₅₀ = 5 µm and a specific surface area of 9 m² g⁻¹. PR2 was a commercially available product with 12.6% total P, 85% apatite, and 11% calcite with a d₅₀ = 2 µm and a specific surface area of 29 m² g⁻¹ was obtained by grinding. The TSP used was a commercial-grade fertilizer.

Soil incubation study

The first experiment in our attempt to reject H₁, was a soil incubation trial to compare how synthetic hydroxyapatite, positive control using TSP, phosphate rock (PR1), and a negative control compared to each other over time in the soil. Extractable P was measured using Mehlich III, a standard soil test used throughout agriculture and forestry. Diffusive P was measured using Plant Root Simulator probes (PRS© Probe Technology Western AG, Saskatoon, CAN). This study
collected a forest acidic sandy soil sample from the top 20 cm-depth at a loblolly pine (*Pinus taeda*) plantation established in 2000, Hilliard, Florida, USA. The soil collected and used is a sandy Spodosol, Chaires Series (sandy, siliceous, thermic Alfis Alaquods). The soil sample was air-dried and ground to pass 2 mm in size. The pertinent soil properties were pH (H$_2$O) = 4.9, OM = 2%, M3 = 0.6 mg P kg$^{-1}$, sand = 94% and clay = 2%. P sources used were HA, PR1, and TSP. Each P source was thoroughly mixed with 100 g of soil at an equivalent field rate of 87 kg P ha$^{-1}$. A control without P added was included in the treatments. The soil samples were incubated at field capacity. The containers were opened weekly to ensure adequate aeration and maintain soil moisture during the incubation at 1, 3, 7, 14, 21, 56, 90, and 125 days with three replications for each treatment. After each time interval, a 5-g soil sub-sample was taken and extracted with 50 mL of M3 for 5 minutes, followed by filtration. The P concentration of the filtrate was determined as described previously. Another set of samples with 650 g of soil was thoroughly mixed with each P source of HA, PR1, and TSP at the same P rate used previously. Three resin membrane strips were buried in each soil microcosm using the same treatments as M3 and incubated under previously described conditions. Resin samples were extracted simultaneously as the M3 samples except for day 56 and day 125. After each time interval, the three resin strips were combined as a single composite resin strip sample, and the resin-adsorbed P was analyzed after eluting with 0.5 mol L$^{-1}$ HCl (Hangs et al. 2004). The eluant was analyzed for P using an inductively coupled plasma optical emission spectrometry analyzer (Perkin Elmer ICP-OES 8300). While this approach is not replicated, the low variation observed in the Mehlich III extractions between microcosms using the same treatments would suggest a similar low variation using this method and thus, the trends presented have merit in being discussed.

**Soil solubility experiment**

H$_2$ tested the solubility of each of the compounds. This experiment used all the previous treatments; however, we introduced PR2 as a general comparison to PR1 because it had a similar particle size but nearly double the amount of P content (85% vs. 49%). The higher P content of this rock was considered promising for agronomic trials and was thus included in the solubility experiment due to having a similar p-content to the HA compound. The P sources used were HA, PR1, PR2, and TSP. Three replicates were made with each solubility measurement. A buffered solution of 2% citrate was prepared from citric acid, trisodium citrate dihydrate, and demineralized water. Two solutions were designed by adjusting the pH by adding concentrated NaOH solution to obtain the desired pH of 3 and 6. A sample of 0.10 g of each P source was extracted with 150 mL of citrate solution by a shaker for one hour at 25°C, followed by filtration on a 0.2 μm syringe filter. The ammonium molybdate-ascorbic method determined the P concentration (Murphy and Riley 1962).

**Greenhouse study**

To test our third hypothesis, H$_3$, we tested the growth potential of each compound, excluding PR1, on the *Eucalyptus globulus* in a greenhouse growth experiment. From the results of the solubility experiment, we decided to use PR2 as opposed to PR1 for our growth experiment, considering PR2 had higher solubility and an overall higher apatite content than PR1. This was a deliberate choice considering time constraints and the probability of success, and PR2 had more promising field applications than PR1. A similar soil that was also P-limited was substituted for the greenhouse study due to a lack of available material. The soil used was forest soil collected in the northern part of Italy. Pertinent soil properties were pH (H$_2$O) = 4.9, organic matter =12.2%, CEC = 5.3 cmol kg$^{-1}$, sand =73.9%, clay =5.2%, silt= 20.9%. This experiment used five P treatments: Control, TSP, PR2, HA, and mixed (HA + PR2) at a 50:50 weight ratio. HA and PR2 were combined to determine whether increasing the total available calcium and phosphorus released from each source in the soil influenced the growth of *Eucalyptus globulus*.
Table 1. Mehlich 3 extracted phosphorus over a 125 day incubation.

| Treatments | Day 1 | Day 3 | Day 7 | Day 14 | Day 21 | Day 56 | Day 90 | Day 125 |
|------------|------|------|------|-------|-------|-------|-------|--------|
| CON        | 0.51 (0.1) b<sup>1</sup> | 0.54 (0.1) b | 0.94 (0.4) c | 1.55 (0.1) b | 1.51 (0.1) b | 2.01 (0.1) b | 2.35 (0.2) c | 2.49 (0.1) c |
| HA         | 6.98 (0.3) a | 7.98 (0.6) a | 5.11 (0.4) bc | 9.41 (0.5) a | 9.76 (0.2) a | 10.7 (0.5) a | 10.0 (0.3) ab | 9.10 (0.8) ab |
| PR1        | 6.36 (0.5) a | 8.75 (1.0) a | 9.90 (1.6) a | 9.76 (1.1) a | 8.74 (0.5) a | 10.8 (0.2) a | 11.4 (1.1) a | 11.5 (0.9) a |
| TSP        | 7.12 (0.3) a | 7.50 (1.4) a | 7.34 (1.4) ab | 10.2 (0.6) a | 9.74 (0.2) a | 11.4 (0.5) a | 7.34 (0.9) b | 7.5 (0.6) b |

Statistics Pr>F <0.0001 0.001 0.0012 <0.0001 <0.0001 <0.0001 0.0001 0.0002

<sup>1</sup>Letters within columns that are the same are not significantly different at p-value < 0.05 using Tukey’s HSD.

Statistics

For the soil incubation experiment, results were derived using the Proc Glimmix procedure in SAS 9.4. The analysis was conducted and was performed per destructive sample period. Treatment is a fixed effect, and replicates were treated as random effects. In all cases, treatment (P source) was a significant factor. A least-squares means comparison was performed using Tukey’s adjusted Post Hoc analysis, alpha value 0.05, to determine treatment differences between M3 soil tests for each sample period and Resin soil tests for each sample period (Table 1). Soil incubation study was performed using JMP Pro 16 using a standard least-square means treating P source solubility as our dependent variable. In our greenhouse trial, we analyzed the overall growth effects of each of our treatments as fixed effects and replicates as random and determined any differences in mean using Tukey Kramer Post Hoc analysis at an alpha value of 0.10. Effects were not significant using an alpha value of 0.05.

Results and discussion

Soil incubation study

Because M3 is a very acidic reagent, it dissolves both soluble and insoluble forms of P. In other words, M3 is an excellent indicator of the amount of P present in our experiment, regardless of whether it is available to the plant itself. Since the investigation was controlled for P applied with each compound, it confirms that at day 0, M3 could successfully determine the amount of P applied as all three compounds applied fell within 6 mg P kg<sup>−1</sup>. In contrast, the control soil registered close to 0 mg P kg<sup>−1</sup> (Figure 2). All three compounds had similar levels of extractable phosphorus at day 60 and were significantly higher than the control (p-value < 0.05). By the end of the experiment on day 125, multiple comparisons revealed significant differences between the treatments (Table 1). At this point, we assume that the soil’s sandy, low P-fixing capacity began to highlight the differences between the three compounds as the more soluble each compound was, the more P would be lost in the system with subsequent watering to maintain soil moisture levels. By the end of the experiment extractable P was highest for PR1 (p-value < 0.05), followed by HA and TSP, which were not significantly different from one another, but all higher than the control. This could indicate that TSP and HA had higher diffusivity levels due to their increased solubility causing P to leach out of the sandy soil steadily. In contrast, the PR1 overall had less soluble phosphorus and thus continued to maintain relatively high testing levels. M3 is already known to overestimate for PR (Menon and Chien 1995).

To confirm that each phosphorus source was releasing phosphorus correlating with their various solubility, resin exchange membranes designed to test for diffusive phosphorus were used to determine the cumulative amount of resin-P overtime released from each testing compound (Figure 3). The data we received from the resin probes confirmed that by day 90, treatments were significantly different from one another. TSP released the most diffusive phosphorus by day 90, followed by HA, PR1, and finally, the control (p-value < 0.05). Results confirm our hypothesis H<sub>3</sub> that synthetic hydroxyapatite released more diffusive phosphorus over time than PR1 but still significantly less than TSP. To follow up and ensure these results, we tested each compound in a controlled environment to determine the solubility of each of our tested compounds.

Solubility test study

The solubility of each P-containing fertilizer product is shown in Table 2. The solubility values of all P sources expressed by % of total P ranged from 80% to 98% of total P in citrate pH 3 solution and 46% to 93% of total P in citrate pH 6 solution. The high solubility of the two PR sources as % of total P in citrate pH 3 solution can be explained by the solid: solution ratio chosen in this study at 0.10 g/1500 mL = 1 g/1500 mL (Chien and Hammond 1978). The solubility values...
expressed in % of the solid weight and considering the total P to eliminate the P grade effect on solubility expression that favors low-grade P source mathematically reveal a more realistic comparison of the solubility of the different products (Table 2). P solubility of HA and PR2 based on % of solid is comparable and higher than PR1 for pH 3. PR1 and PR2 had a nearly 50% reduction of soluble P from pH 3 to pH 6, while the solubility of HA remained constant regardless of pH change, indicating that HA is buffered against fluctuations in pH. Results from this experiment conform with results from the soil incubation experiment that showed significantly higher amounts of diffusive and extractable P present in HA than PR1. However, considering PR2 was not used in the soil incubation experiment we cannot say for certain that HA would have higher levels of extractable and diffusive P. Thus, we can only partially accept our 1st hypothesis and only extend our results to compounds similar to PR1. We can, however, confirm that HA had overall higher solubilities than both PR1 and PR2 for both pH 3 and pH 6, confirming our second hypothesis.

It is well established that the solubility of water-insoluble P compounds can be substantially increased by decreasing particle size and thus increasing surface area (Lim et al. 2003). The very high solubility of HA in citrate pH 6 could also be due to the solid: solution ratio used since it is known that HA is only partially soluble in neutral citrate solution (Wier et al. 1971). More likely, the total solubility of the synthetic HA in citrate pH 6 solution can be explained by the high porosity and the lamellar structure of the HA in the sub-micron range (6.6 μm) (Figure 1(a)). The structure and the related high specific surface area of 53 m² g⁻¹ could explain the high reactivity of standard HA with a smaller surface area below 10 m² g⁻¹.

The high solubility of the synthetic HA is demonstrated in Figure 1(b), which shows that all the HA (lamellar structure) is dissolved after only 15-min exposure to citric acid pH 6. As can be seen, the lamellar structure of HA is entirely dissolved after a short period, revealing the core of the mineral conglomerate formed of CaCO₃. The high reactivity of the material lets us assume that this material can release P from the lamellar structure in soils up to a pH of 6. To reiterate, depending on the source and configuration of common mined phosphate rock, higher pH values in the surrounding medium generally reduce the solubility of the medium making our HA a unique compound (Chien 1993).

Greenhouse study

HA-grown Eucalyptus globulus had overall had significantly higher Combined Dry-Matter yield (biomass + Roots), Shoot Length in cm, and Dry-matter (Roots) than the Control and PR2 (p-value <0.10) (Table 3). TSP failed to increase the plant’s root or shoot biomass grown under the same conditions. Knowing from our incubation tests that phosphorus was indeed a soil limiting factor in these experiments (Figures 1 and 2) based on the control values. The lack of the expected fertilizer response on growth from TSP application and associated P is probably due to uncontrolled variables in our experiment and the native soil characteristics. It is possible that high soil acidity (pH 4.9) could have negatively affected the availability of P within our trials. Yang et al. (2015) reported that soil acidity stresses significantly adversely affected the
photosynthetic activity of *Eucalyptus* seedlings in growth. Unfortunately, no pH data was collected from the soil medium, so this could not be confirmed. The TSP was more readily available in its soluble form than the other treatments for uptake and allocated to above-ground biomass instead of enhanced root growth. The shoot length data suggest that this idea could be partially true, although no destructive above-ground biomass was sampled for P.

The lack of a DMY response to PR2, which contained 11 mg kg\(^{-1}\) CaCO\(_3\) suggests the liming effect of minimal effect on plant growth. However, HA had significantly more CaCO\(_3\) 25 mg kg\(^{-1}\) than the PR2, which could have caused a more significant liming effect raising the total soil pH so that phosphorus was more available to the plant. The observation supports the fact the TSP treatment had little to no impact on Combined Dry-matter yield (Table 3) even though it has the highest solubility across pH levels (Table 2). This result implies that P was not the limiting factor present in the experiment. The CaCO\(_3\) present in the PR2 and HA did not have a control group and thus can only be speculated upon. It is believed that CaCO\(_3\) could positively affect *Eucalyptus* growth by increasing the soil’s pH and supplying calcium to the plant (Grover et al. 2021). As demonstrated in the solubility trial, the HA will quickly dissolve the HA lamellar structure leaving the CaCO\(_3\) core of the particle (Figure 4(b)). The remaining CaCO\(_3\) will then react with the acidity in the soil reacts with soil contributing to increasing the pH and calcium supply, which will increase the availability of phosphorus, increasing in availability as pH increases. In addition, the effect of HA compared to the PR2 can be explained by the high P solubility (Table 2). While not significant, the numerically higher DMY of (HA + PR2) than that of PR2 may be due to the higher P solubility since the amounts of CaCO\(_3\) added to the soil were about the same (Table 3). It is thus hypothesized that the combined effects of CaCO\(_3\) and P solubility of different P sources were responsible for the significantly more significant growth of *Eucalyptus* seedlings in the HA treatments as observed in the greenhouse experiment, compared to the more commonly used TSP fertilizer.

Concerning the effect of HA’s application compared to TSP and PR2, the most exciting difference is found in effect on the root growth, especially the fine root development, as demonstrated in Figure 4. Exemplified by the roots extracted at the end of the trial, the addition of HA had a stimulating effect on root growth and especially the fine roots (\(p\)-value <0.10) (Table 3). Calcium results on fine root growth are mixed and often vary by site (Park et al. 2008; Fahey et al. 2016). However, in vitro studies have demonstrated the potential growth effects of calcium on *Eucalyptus sp.* (Arruda et al. 2000). A previous study using HA in *Solanum lycopersicum* showed similar growth responses to root elongation and plant vigor, explaining why we observed such substantial root development in the HA treatments (Marchiol et al. 2019). The issue comes with differentiating between the liming effect that CaCO\(_3\) provides, increasing the availability of other nutrients, or that of Ca itself. In this case, where we have highly acidic soil, both factors are significant when fertilizing with HA. In addition, the effect of HA itself could explain the observed root development.

Overall, a combination of phosphorus and calcium had a significant role in the successful differences of the synthetic hydroxyapatite in our experimental design. Although we were primarily concerned with phosphorus effects initially, it soon became apparent that solubilized calcium from the HA on our acidic soils might have had a more pronounced effect on plant growth than we originally expected. Future research on this compound and careful redesigning of

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### Table 2. Total P and solubility of the four products tested.

| P Source | Water Solubility | Total P (%) | Soluble P (% of Solid) | Soluble P (% of Total P) |
|----------|------------------|-------------|------------------------|--------------------------|
|          |                   |             | Citrate pH 3           | Citrate pH 6             | Citrate pH 3 | Citrate pH 6 |
| TSP      | Soluble          | 20.0        | 19.6 (7.54E-03)        | 18.6 (6.38E-03)          | 98 (9.23E-03)| 93 (4.38E-03) |
| PR1      | Insoluble        | 5.9         | 5.8 (1.91E-02)        | 2.7 (1.61E-02)          | 98 (2.01E-02)| 46 (3.58E-02) |
| PR2      | Insoluble        | 12.6        | 10.0 (2.48E-02)       | 6.3 (1.66E-03)          | 80 (1.42E-02)| 50 (7.56E-03) |
| –HA–PR2 | Insoluble        | 10.4        | 9.9 (1.16E-02)        | 6.3 (2.31E-02)          | 95 (4.22E-02)| 92 (1.21E-02) |

HA had comparable solubility to TSP as a percentage of total P. The percentage of solid P found in HA was much lower than TSP, similar for PR2, and lower for PR1. The solubility of HA was minimally affected by raising the pH to 6, while PR1 and PR2 had substantial decreases in solubility of

### Table 3. Effects of synthetic hydroxyapatite on root and shoot elongation.

| P Source | CaCO\(_3\) Added\(^{-1}\) (g pot \(^{-1}\)) | Combined dry-matter yield \(^{-1}\) (Biomass + Root), gpot\(^{+}\) | Dry-matter \(^{-1}\) Yield Root, gpot\(^{+}\) | Shoot length (cm\(^{+}\)) |
|----------|------------------------------------------|-------------------------------------------------|---------------------------------|------------------|
| Control  | –                                        | 552b                                           | 163b                           | 639b             |
| TSP      | –                                        | 562b                                           | 173b                           | 718ab            |
| PR2      | 2.2                                      | 561b                                           | 170b                           | 654b             |
| HA       | 5                                        | 666a                                           | 214a                           | 801a             |
| (HA + PR2) (50:50) | 2.6                                | 612ab                                          | 197ab                          | 725ab           |

The effect of applying different P sources and associated CaCO\(_3\) on average dry-matter yield (DMY) and shoot length of *Eucalyptus globulus* seedlings grown for 154 Days. Cumulative shoot length is determined by adding the shoot length for all individual shoots of one seedling after destructive sampling at day 154.

\(^{+}\)Values with the same letter are not significantly different at \(p \leq 0.10\).
our experiment need to be performed to determine the differences between the liming effect of the additional calcium and the phosphorus provided by the HA compound. Altogether, the HA compound we currently tested appears to be a great candidate for applications on acidic soils for growing Eucalyptus globulus. However, more research, specifically field trials, needs to be conducted before operational applications can be considered.

**Conclusions**

This study demonstrates the potential for applying a novel synthetic-HA containing mineral as starter fertilizer in production forestry on highly acidic, low reactivity sites with the potential for root stimulating growth. The results show that the available P measured by resin-P in the acid sandy forest soil treated with synthetic HA was as high as TSP and more readily soluble and, thus, available than that from reference rock samples PR sources. In addition to the high solubility of synthetic HA and the expected fertilization effect from P, the associated CaCO₃ in the HA product appeared to have an impact on growth and needs to be explored in later experimentation.

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**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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