EFFECTS OF NANO-SiO_2, Nd_2O_3 AND CeO_2 ON THE GROWTH OF *Paramignya trimera* (Oliv.) AND *Paris polyphylla*

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ABSTRACT

The study investigated nano-SiO_2, Nd_2O_3, and CeO_2 materials applied as fertilizer for *Paramignya trimera* (Oliv.) Guill plants. (Rutaceae) and *Paris polyphylla*. The cultivation results indicated that the individual uses of nano-SiO_2, Nd_2O_3, and CeO_2, respectively, induced stem and root growth of *P. trimera* and *P. polyphylla*. The plant height, root length, stem, and root weight of the mixture of Nd_2O_3 and SiO_2 or CeO_2 and SiO_2 exposed plants were greatly higher than those of the individual nanomaterial exposed plants. The extraction experiments indicated that ostruthin, a valuable medicinal substance, accumulated in the roots of the *P. trimera* rather than in its stems. The ostruthin content in the root of the Nd_2O_3 exposed *P. trimera* was also greatly higher than that in the control and SiO_2 exposed plants. Gracillin, an important medicinal compound, content in the rhizome of the CeO_2 exposed *P. polyphylla* was also greatly higher than that in the SiO_2 exposed *P. polyphylla*.

Keywords: *P. trimera, P. polyphylla*, ostruthin, gracillin, nano-fertilizer, synergic effects, nano-SiO_2, nano-Nd_2O_3, nano-CeO_2.

1. INTRODUCTION

Silicon has never been classified as a vital nutrient for plants because most plants don't require the element for their survival [1]. However, various plants effectively utilize the element for their development and resistance against biotic and abiotic factors [2]. Manzer H.S. and Mohamed H.A.W. stated that silicon would exist in the epidermis walls and vascular bundles of stems, plants' hull and leaf sheath to create physico-mechanical barriers for plant protection [1]. The existence of silicon also induced the nutritional absorption ability of many different plants. For instance, Kaya and coworkers reported that under abiotic stress, silicon in corn efficiently improved Ca and K adsorption of the plant [3]. To apply as fertilizer, silicon is usually used in the form of silicon oxide before mixing with the cultural solution or adding to the cultivating field [4].

In recent years, rare earth elements (REEs), which are Group IIIB elements of the periodic table, containing Sc, Y and 15 lanthanide elements (La, Pm, Ce, Pr, Tm, Nd, Tb, Sm, Eu, Gd, Ho, Dy, Er, Yb, Lu), has been rapidly applied, in particular, in industrial and agricultural sectors [5]. Fertilizers enriched with rare earth element oxides, including La_2O_3, Nd_2O_3, CeO_2, Pr_6O_{11}, Sm_2O_3, and Eu_2O_3, have been studied and broadly applied for several decades in agriculture [6]. Fertilizers containing rare earth elements would be applied to leaves, seeds, and roots to increase the growth and productivity of plants [7]. This is due to rare earth elements could improve the uptake and accumulation of nutrient elements, water use, membrane stability, and photosynthesis of plants [8, 9]. For example, the presence of Y reduced the length and width of stomata to prevent water loss in plants [10]. Hong et al. reported that the Ce^{3+}, Nd^{3+}, and La^{3+} promote growth and increase the chlorophyll content in the plants, leading to an increase in their photosynthesis [11]. Hu et al reported that the first commercial rare earth element fertilizer containing La_2O_3 (25–28%), CeO_2 (49–51%), and Nd_2O_3 (15–17%), which was named "Changle", was registered in China in 1986 [12]. Mixed rare earth element oxides, including La_2O_3 (25–28%), CeO_2 (49–51%), Nd_2O_3 (14–16%), Pr_6O_{11} (5–6%), have been used as fertilizer for Chinese cabbage and rapeseed [13]. Authors reported that the used mixtures improved crop yields and decreased diseased plant amounts; however, the effects of each oxide have not been identified.

Paramignya trimera (*P. trimera*), a well-known medicinal plant in Vietnam and Thailand for the treatment of numerous cancers, will be selected as the experimental plant [14]. Ostruthin, a major geranylated coumarin, accumulating in stems and roots of the *P. trimera*, has been considered as emerging natural medicine for cancer treatment because it exhibited moderate cytotoxicity against epithelial cervical carcinoma (Hela) and hepatocellular carcinoma (Hep-G2) cell lines with half maximal inhibitory concentration -(IC_{50} values) of 5.36 and 39.61 μg/mL, respectively [14, 15].

Paris polyphylla (*P. polyphylla*) is considered a vital herb in China, India, and Indochina to use as traditional medicine [16]. The *P. polyphylla* has been widely used for the direct treatment of back pain, bleeding, and even cancers [17]. The *P. polyphylla* is also used as an important material for topical medicaments of carbuncles, traumatic pain, sore throat, and poisonous snake bite treatment [18]. Gracillin (GR) (diosgenin-3-O-β-D-glucopyranosyl-(l→3)-(α-L-rhamnopyranosyl-(l→2))-β-D-glucopyranosid), which accumulates in the *P. polyphylla* rhizome, is a useful medicine for the treatment of stomach cancer [19]. Thus, the study not only inspects the effects of nano CeO_2 and SiO_2 on promoting the *P. polyphylla* development but also clarifies the gracillin amounts in its rhizome to acutely explore the effects of the nano particles for the formation of the treasured medicine in the plant.

2. MATERIALS

The nano-SiO_2, nano-Nd_2O_3, and nano-CeO_2 were synthesized in the laboratory. The size of particles was determined by TEM images. The mean size of the SiO_2 was approximately 50 nm. The synthesized Nd_2O_3 was sharp particles with an average size of approximately 150 nm. The synthesized CeO_2 was an agglomeration of approximately 10 nm-sized particles on average.

3. PLANT CULTIVATION AND GROWTH DETERMINATION

The experiments of *P. trimera* were performed from December 2022 to November 2023 at the research farm belonging to Quy Nhon University, Binh Dinh, Vietnam. The annual rainfall at the experimental site is 2617 mm, with an average temperature range from 25 to 32 °C. The *P. trimera* was cultivated in four randomized plots. Each plot was 30 m^2. Four plots with four different treatment conditions, including control (naturally grown without any nanomaterial application), nano-SiO_2, nano-Nd_2O_3, and mixture - (SiO_2:Nd_2O_3 weight ratios were 1:1) fertilizers, were carried out. For fertilization, 1.0 g of nanomaterial was suspended in 1.0 L of chitosan solution (500 ppm) before diluting in water to obtain a solution with a nanomaterial concentration of 4 ppm. Chitosan was used as a stabilizer to disperse SiO_2 and Nd_2O_3 oxide to form a stable colloid before spraying on plants [20, 21]. Then, the obtained solution was sprayed by foliar (360 L/ha) on the first cultivation day. No other fertilizer and irrigation activities were conducted during the entire cropping period. At interval times of 4 months, six plants of each plot with intact roots were removed from the soil carefully. After that, plants were gently rinsed four times with tap water to remove the attached dust. The rinsed plants were naturally dried at room temperature for 1 day. Height, stem weight, root length/weight of dried plants were measured and recorded.

The experiments of *P. polyphylla* were executed from December 2023 to May 2024 at a field located in An Toan Hamlet (14◦31′55.4″ N, 108◦41′01.9″E), An Lao Village, Binh Dinh Province, Vietnam. Yearly rainfall and average temperature at the experimental location are 2617 mm and 25 - 32 ºC, respectively. The *P. polyphylla* saplings, which were purchased from An Toan Agro-pharmaceutical & General Services Cooperative located at Binh Dinh Province, the major distribution area of the *P. polyphylla* in Vietnam, were cultured in four randomized plots. Each plot was 30 m^2. Four cultivation conditions, including controlled conditions (natural development), individual REE oxides, and mixture (SiO_2: CeO_2 with wt ratios of 1:1), were executed [16]. To create a fertilizing solution, nanomaterial was mixed with chitosan solution (500 ppm) to obtain a suspension, with a nanomaterial concentration was 1000 ppm. Then, the suspension was continuously diluted with tap water to achieve a fertilizing solution, with a concentration of nanomaterials was 4 ppm. The obtained fertilizing solution was foliar sprayed across the field (360 L/ha) on the first cultivation day. Throughout the whole cultivation season, no additional irrigation or fertilizer applications were made. After 60 days, six plants (including roots) of each plot were carefully removed from the experimental field. Then, plants were washed carefully with tap water four times to eliminate remaining dust [18]. Acquired plants were left dry spontaneously at ambient temperature for a day. Plant height, stem diameter, leaf area, and rhizome weight of dried plants were measured and documented.

4. OSTRUTHIN AND GRACILLIN ANALYSIS

4.1. Ostruthin analysis

The extraction of ostruthin from *P. trimera* roots and stems was conducted according to the method described by Trinh et al. (2020) [22]. In detail, dried and ground roots (or stems) of the *P. trimera* (after 12 months of cultivation) were exhaustively extracted with methanol using a Soxhlet extractor. Then, the extracted solution was filtered before analysis using a High-Performance Liquid Chromatography (HPLC 1260, Agilent). The HPLC was equipped with a G1311C quaternary pump, G2260A autosampler, and DAD-G1315D diode array detector. Chromatographic separation was achieved on an XDB-C18 column (150 × 4.6 mm, 5 µm; Agilent). Mobile phases were acetonitrile and 0.1% formic acid. The flow rate was maintained at 0.5 mL/min. The DAD collected data from 200 to 400 nm.

4.2. Gracillin analysis

Firstly, dried and ground *P. polyphylla* rhizome was thoroughly extracted by CH_3OH using a Soxhlet system. Then, the extraction was analyzed using a high-performance liquid chromatography (HPLC 1270, Agilent) to determine gracillin concentration. The HPLC was equipped with a G1310C quaternary pump and a G2290A autosampler. An XDB-C18 column (150 × 4.6 mm, 5 µm; Agilent) was used for chromatographic separation. The mixture of acetonitrile and 0.1% formic acid was used mobile phase. The flow rate was 0.5 mL/min. The system used a DABG1315B detector, and the detection wavelength was set at 200 nm. The LOD and LOQ were 0.02 (µg/mL) and 0.07 (µg/mL), respectively. The standard curves were linear over the concentration range of 1–80 µg/mL.

5. RESULTS AND DISCUSSION

Figure 1 shows digital graphs of the *P. trimera* under control conditions (natural growth without any nanomaterial application) and after 12 months exposed nanomaterials. It can be seen that the applications of nano-SiO_2 and nano-Nd_2O_3, as well as their mixture, significantly induced the growth of the *P. trimera*. This could be due to the used SiO_2 and Nd_2O_3 could pervade plants through roots and aboveground tissues to strengthen the physical barrier as well as to activate the defense systems of plants [23]. The used nanomaterials would also improve uptake and accumulation of nutrients, water use, membrane stability, and photosynthesis of the *P. trimera*, leading to its great growth [11].

Figure 1. Digital graphs of the *P. trimera* under different exposed conditions: (a): Control, (b): SiO_2 exposed plant, (c): Nd_2O_3 exposed plant, (d): Mixture SiO_2 and Nd_2O_3 exposed plant

Table 1. Plant height, root length, stem, and root weight of *P. trimera* under different conditions and exposure times

Factors	Conditions	Exposure times (months)				
		0	3	6	9	12
Plant height (cm)	Control	35.6 ± 0.8	38.3 ± 1.4	45.9 ± 1.6	49.5 ± 1.5	52.1 ± 1.9
	SiO_2	35.6 ± 0.8	42.8 ± 1.7	49.1 ± 2.1	53.5 ± 2.2	57.6 ± 2.3
	Nd_2O_3	35.6 ± 0.8	40.5 ± 2.1	47.8 ± 2.3	52.1 ± 2.5	55.2 ± 2.7
	Mixture	35.6 ± 0.8	45.4 ± 2.3	52.9 ± 2.6	58.5 ± 2.8	62.8 ± 2.9
Stem weight (g)	Control	29.7 ± 1.3	36.9 ± 1.6	45.3 ± 2.1	55.2 ± 2.2	60.9 ± 2.4
	SiO_2	29.7 ± 1.3	45.1 ± 1.9	59.4 ± 2.7	72.2 ± 2.5	78.3 ± 3.6
	Nd_2O_3	29.7 ± 1.3	41.8 ± 1.8	55.9 ± 2.5	66.1 ± 2.6	71.2 ± 2.9
	Mixture	29.7 ± 1.3	46.8 ± 2.4	66.1 ± 3.1	76.5 ± 3.1	83.1 ± 3.6
Root length (cm)	Control	7.3 ± 1.1	8.8 ± 1.1	12.1 ± 1.4	14.8 ± 1.2	16.5 ± 1.3
	SiO_2	7.3 ± 1.1	10.2 ± 1.4	15.1 ± 1.6	18.2 ± 1.3	20.6 ± 1.5
	Nd_2O_3	7.3 ± 1.1	12.5 ± 1.4	17.5 ± 1.7	21.4 ± 1.6	24.3 ± 1.4
	Mixture	7.3 ± 1.1	14.7 ± 1.2	22.4 ± 1.9	26.1 ± 1.8	29.4 ± 1.7
Root weight (g)	Control	4.1 ± 0.3	7.4 ± 0.5	13.4 ± 0.8	15.8 ± 0.6	19.7 ± 0.7
	SiO_2	4.1 ± 0.3	9.5 ± 0.6	16.8 ± 0.7	19.3 ± 0.8	21.5 ± 0.9
	Nd_2O_3	4.1 ± 0.3	12.9 ± 0.8	18.9 ± 0.9	22.5 ± 0.8	25.2 ± 1.1
	Mixture	4.1 ± 0.3	16.2 ± 1.1	21.4 ± 0.9	25.3 ± 1.1	28.2 ± 1.6

In detail, the growth of *P. trimera* was monitored by measuring its height, root length, stem, and root weight under different conditions and exposure times shown in Table 1. The obtained results are also plotted in Figure 2 to clarify the effects of nano-SiO_2 and nano-Nd_2O_3 on the growth of the *P. trimera*. It can be seen that the applications of nano-SiO_2 and Nd_2O_3 exhibited different effects on root and stem growth of the *P. trimera*. Firstly, individual applications of both nano-SiO_2 and nano-Nd_2O_3 effectively induced stem growth of the *P. trimera*. The height of the Nd_2O_3-exposed plant was 55.2 cm, which was approximately 5.9% higher than the height of the control plant. The stem weight of the Nd_2O_3-exposed plants was 71.2 g, which was also approximately 16.9% higher than the stem weight of the control plant. In addition, as compared to the nano-Nd_2O_3 application, the nano-SiO_2 application significantly induced stem growth of the *P. trimera*. Significant improvement was noticed in plant height (~ 4.3%) and stem weight (~ 10.0%) due to the nano-SiO_2 application over the Nd_2O_3 application. This indicated that the SiO_2 application greatly induced stem growth of the *P. trimera* rather than the Nd_2O_3 application. Regarding root growth, the root length and root weight of the SiO_2-exposed *P. trimera* were 20.6 cm and 21.5 g, respectively, which were greater than those of the control plant. Significant improvement was noticed in root length (24.8%) and root weight (9.1%) due to the nano-SiO_2 application over the control. However, the root length of the Nd_2O_3-exposed plant was 24.3 cm, which was approximately 18.0% higher than the root length of the SiO_2-exposed plant. The root weight of the Nd_2O_3-exposed plants was 25.2 g, which was also approximately 17.2% higher than that of the SiO_2-fertilized plant. This indicated that the Nd_2O_3 application greatly induced root growth of the *P. trimera* rather than the SiO_2 application. Finally, the combination of applications of Nd_2O_3 and SiO_2 greatly induced stem and root growth of the *P. trimera*. The plant height, root length, stem, and root weight of the mixture-exposed plant were greatly higher than those of the individual nano-material exposed plants. This opens a new era on the combination application of nano-SiO_2 and nano-Nd_2O_3 for the growth of as well as other medicinal plants.

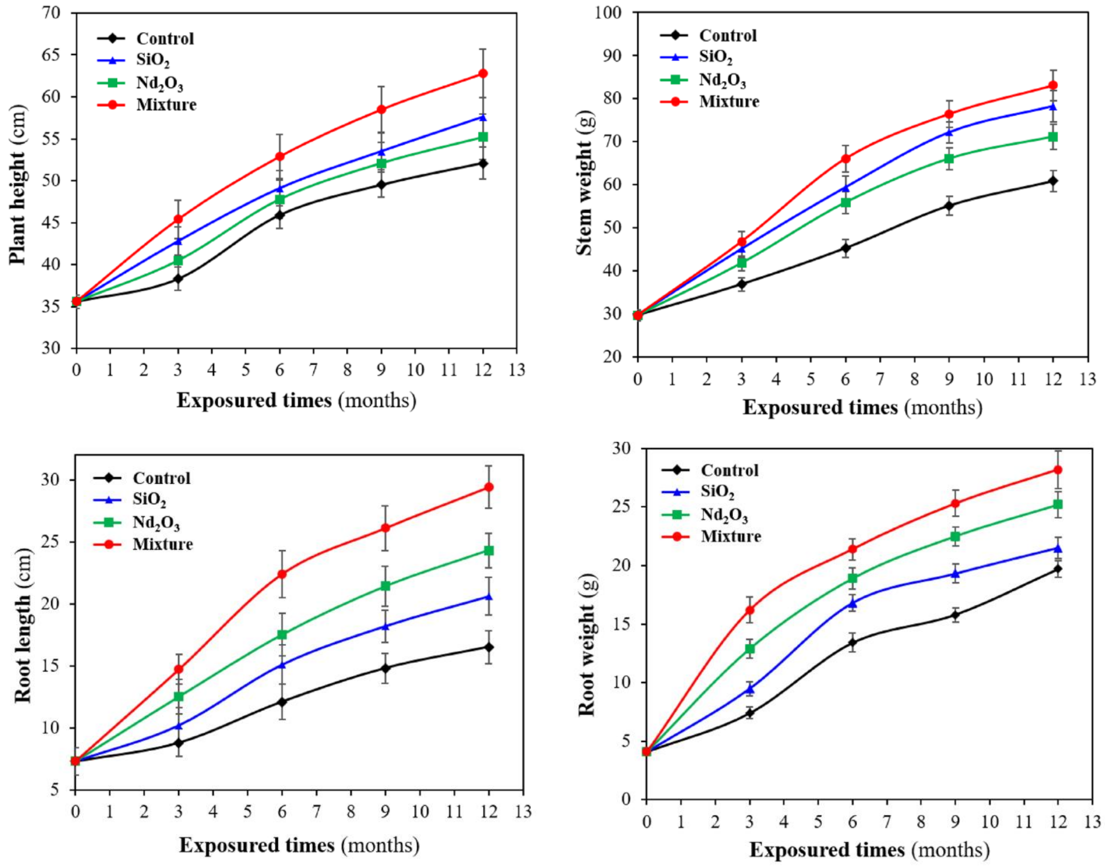

Figure 2. Plant height, root length, stem, and root weight of *P. trimera* under different conditions and exposure times

Table 2. Ostruthin contents in the roots and stems of the *P. trimera*

	Ostruthin contents in the P. *trimera* (%)			
	Control	Exposed SiO_2	Exposed Nd_2O_3	Exposed mixture
In roots	1.713 ± 0.024	1.789 ± 0.028	2.121 ± 0.039	2.206 ± 0.041
In stems	0.003 ± 0.001	0.003 ± 0.002	0.004 ± 0.002	0.004 ± 0.001

The ostruthin contents in roots and stems of the cultivated *P. trimera* are presented in Table 2. It can be seen that ostruthin accumulated in the roots of the *P. trimera* rather than in the stems. This agreed with recent reports on ostruthin extraction from the *P. trimera* [24]. The ostruthin content in the roots of the control *P. trimera* was approximately 1.713%. When SiO_2 was used as fertilizer, the ostruthin content in the roots of the *P. trimera* was 1.789%, which was slightly higher than that in the control plant. This indicated that the use of SiO_2 nanomaterial slightly induced ostruthin formation in the *P. trimera*. However, when Nd_2O_3 was fertilized for the *P. trimera*, the ostruthin content in the roots of the plant was approximately 2.121%, which was greatly higher than that in the control plant (higher than 23.8%) as well as in the SiO_2-exposed plant (higher than 18.5%). This indicated that the Nd_2O_3

nano-materials not only induced root growth but also aided the accumulation of ostruthin in the roots of the *P. trimera*. Finally, when the mixture of Nd_2O_3 and SiO_2 was fertilized for the *P. trimera*, the ostruthin content in the roots of the plant was approximately 2.206%, which was slightly higher than that of a single Nd_2O_3-exposed plant. However, the roots of the mixture-exposed *P. trimera* were greatly bigger than those in the Nd_2O_3-exposed plants. Thus, the use of Nd_2O_3 and SiO_2 mixture still exhibited significant advances for the cultivation of the *P. trimera* as an ostruthin extraction plant.

Figure 3 shows digital graphs of the cultivated *P. polyphylla* plots after 180 days. It can be seen that the cultivated *P. polyphylla* grows well. Thus, the development of the *P. polyphylla* was greatly enhanced by the applications of nano SiO_2, nano CeO_2, and their mixture. Specifically, the development of *P. polyphylla* was monitored by appraising plant height, stem diameter, leaf area, and rhizome weight. The obtained results were presented in Table 3 and Figure 4. It can be seen that the use of SiO_2 and CeO_2 created different effects for the development of the *P. polyphylla*.

Figure 3. Cultivated *P. polyphylla* plots after 180 days

Firstly, *Paris polyphylla* exposed to SiO_2 showed significantly greater growth compared to the control. The stem diameter and leaf area of SiO_2-treated plants were also larger. Specifically, plant height, leaf area, and stem diameter were 16.87%, 23.03%, and 14.75% greater, respectively, than those of control plants. These results indicate that SiO_2 significantly enhances the growth of the aboveground parts of *P. polyphylla*. Yashwanth Arcot et al. reported that the surface of a plant's leaves and stems is not smooth [25]. Therefore, a certain amount of used nano materials would be distributed on the leaves and stems of the *P. polyphylla*. When existing in stems and leaves, SiO_2 nanoparticles created a physico-mechanical barrier to protect the plant from its growth. In addition, Alsaeedi et al. reported that plants absorbed SiO_2 nanoparticles via roots and transferred them to the epidermis walls and vascular bundle of stems and leaves [26]. Silicon also enhanced the ultrastructure of leaf cells and reduced electrolyte leakage in the leaves for their development [27]. Kasem et al. reported that SiO_2 also maintained peripheral links between carbohydrates and lignin to aid the uprightness and durability of the leaves [28]. The silicon in plants also improved chlorophyll content, leading to an increase in photosynthesis activity for plant growth [29]. However, the rhizome weight of plants exposed to SiO_2 nanoparticles was only 6.14% higher than that of plants in controlled conditions, suggesting that SiO_2 nanoparticles may not significantly enhance rhizome growth in *P. polyphylla*. In contrast, the rhizome weight of plants exposed to CeO_2 nanoparticles was 14.4% higher than that in controlled conditions, indicating that CeO_2 is more effective than SiO_2 in promoting rhizome growth in *P. polyphylla*. Sonali et al. reported that plants absorbed CeO_2 particles and retained them in the epidermal roots [30]. When existing in the root, CeO_2 provided in a cultural medium accelerates nutrient uptake of roots to significantly improve its growth [31]. Therefore, the rhizome of the *P. polyphylla* exposed CeO_2 greatly developed. However, the average height of *P. polyphylla* exposed to CeO_2 was approximately 7.75% higher than that of plants in controlled conditions. The leaf area and stem diameter of *P. polyphylla* exposed to CeO_2 were 15.7% and 5.7% higher, respectively, compared to those of plants grown under controlled conditions. The obtained results seem similar to reports of Salehi et al., which indicated that CeO_2 nanoparticles significantly induced the development of roots after soil treatment in *Phaseolus vulgaris* L., while they did not induce plant height [32]. Finally, the CeO_2 and SiO_2 mixture significantly promoted stem and root development of the *P. polyphylla*. This was due to the SiO_2-induced growth of aboveground parts such as stems and leaves, while the CeO_2 nanoparticles induced the growth of the rhizome. Thus, the plant height, stem diameter, leaf area, and rhizome weight of the experimental plants, which were exposed to a CeO_2 and SiO_2 mixture, were impressively better than those of the singular nanomaterial-exposed plants. The ANOVA results yield an F-statistic of approximately 123.5 and a p-value of approximately 0.0002, confirming that exposure to SiO_2, CeO_2, or the mixture significantly impacts the growth of *Paris polyphylla* compared to the control conditions. This marks the beginning of a new era in the combined application of nano SiO_2 and CeO_2 for the growth of *P. polyphylla* and other therapeutic plants.

Table 3. Plant height, leaf area, stem diameter, and rhizome weight of *P. polyphylla* with different exposure times and fertilizing.

Factors	Conditions	Exposure times (days)			
		0	60	120	180
Plant height (cm)	Control	10.6 ± 0.5	14.2 ± 0.7	20.2 ± 0.8	27.1 ± 1.1
	CeO_2	10.6 ± 0.5	16.1 ± 0.8	24.5 ± 1.0	29.2 ± 1.3
	SiO_2	10.6 ± 0.5	17.3 ± 0.9	26.9 ± 1.1	32.6 ± 1.5
	Mixture	10.6 ± 0.5	20.4 ± 1.2	30.2 ± 1.3	36.3 ± 1.6
Stem diameter (cm)	Control	0.3 ± 0.02	0.35 ± 0.01	0.43 ± 0.02	0.52 ± 0.02
	CeO_2	0.3 ± 0.02	0.36 ± 0.02	0.45 ± 0.02	0.55 ± 0.03
	SiO_2	0.3 ± 0.02	0.38 ± 0.02	0.53 ± 0.03	0.61 ± 0.03
	Mixture	0.3 ± 0.02	0.42 ± 0.03	0.58 ± 0.03	0.68 ± 0.04
Leaf area (cm^2)	Control	26.3 ± 1.1	30.1 ± 1.2	36.6 ± 1.3	44.1 ± 1.6
	CeO_2	26.3 ± 1.1	33.2 ± 1.4	43.6 ± 1.6	51.5 ± 2.0
	SiO_2	26.3 ± 1.1	38.5 ± 1.4	45.6 ± 1.8	57.3 ± 2.1
	Mixture	26.3 ± 1.1	40.7 ± 1.7	51.5 ± 2.2	62.2 ± 2.5
Rhizome weight (g)	Control	13.1 ± 0.5	16.4 ± 0.7	23.5 ± 1.0	32.1 ± 1.3
	CeO_2	13.1 ± 0.5	19.3 ± 0.8	25.8 ± 1.2	37.5 ± 1.5
	SiO_2	13.1 ± 0.5	17.8 ± 0.8	24.3 ± 0.9	34.2 ± 1.4
	Mixture	13.1 ± 0.5	19.1 ± 0.9	27.4 ± 1.2	41.1 ± 1.7

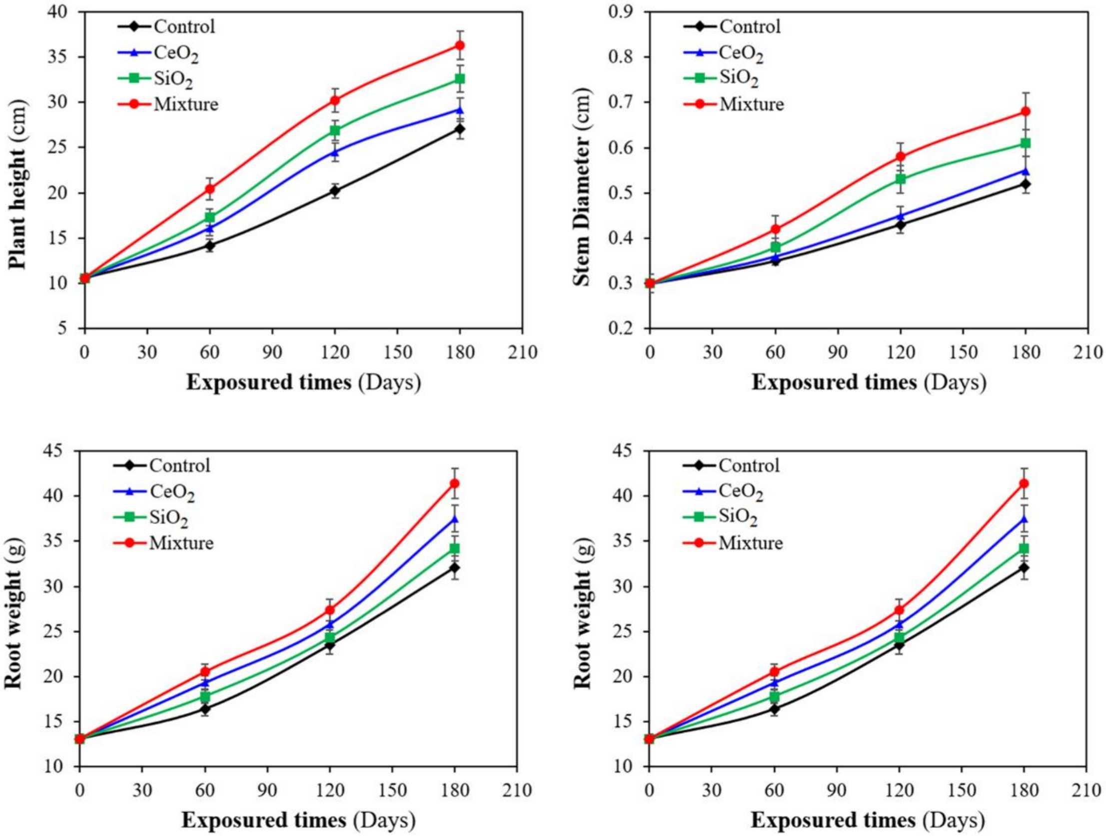

Figure 4. Plant height, stem diameter, leaf area, and rhizome weight *P. polyphylla* under different nurturing conditions and exposure times.

The gracillin contents in the rhizome of the cultivated *P. polyphylla* were shown in Table 4. It can be seen that a significant amount of gracillin is accumulated in the rhizome of the *P. polyphylla*. This was in line with recent results on the extraction of gracillin from the *P. polyphylla* [20]. The gracillin concentration accumulating in the rhizome of the *P. polyphylla* under controlled conditions was roughly 6.9%. When SiO_2 was added to the fertilizing solution, the gracillin content in the *P. polyphylla* rhizome was approximately 7.7%, which is slightly higher than the gracillin content in the plants under controlled conditions. This shows that the SiO_2 nano-material marginally promotes the gracillin formation process in the *P. polyphylla*. However, when CeO_2 was used as fertilizer for the *P. polyphylla*, the gracillin concentration accumulating in the rhizome was around 8.4%, which was greatly higher *P. polyphylla* under controlled conditions (higher than 21.73%) and SiO_2-exposed plant (higher than 9.09%). This observation specified that the CeO_2 nano-material had stimulated rhizome growth and promoted the gracillin buildup process in the rhizome of the *P. polyphylla*. Lastly, when both CeO_2 and SiO_2 nanomaterials were mixed and fertilized for the *P. polyphylla*, the gracillin content calculated from the plant extraction was nearly 9.8%, which was 16.7% higher than that of a single CeO_2-exposed plant. The ANOVA results yield an *F*-statistic of approximately 63.38 and a *p*-value of approximately 6.44E−06. This confirmed that exposure to SiO_2, CeO_2, or the mixture significantly impacts the formation of gracillin in *Paris polyphylla* compared to the control conditions. As compared with other used materials improving growth and gracillin content of the *P. polyphylla*, the used SiO_2 and CeO_2 mixture also exhibited a higher efficiency [33, 34]. In addition, rhizomes of the *P. polyphylla* fertilized by the nano material mixture also have a larger size than those of the CeO_2-exposed plants.

Thus, the combination of CeO_2 and SiO_2 to use as fertilizer exhibited significant advances for *P. polyphylla* cultivation to extract the gracillin component.

Table 4. Gracillin contents in the rhizome of cultivated *P. polyphylla*.

Gracillin contents in the *P. polyphylla* (%)			
Control	Exposed SiO_2	Exposed CeO_2	Exposed mixture
6.9 ± 0.2	7.7 ± 0.2	8.4 ± 0.3	9.8 ± 0.4

The absorption mechanisms of rare earth oxides (REOs) in plants are complex and not as thoroughly understood as those of other metal ions or nutrients. However, research has shown that plants can absorb rare earth elements (REEs), even when introduced in oxide form, through several key processes, including dissolution, chelation, transport, and compartmentalization.

6. CONCLUSION

The SiO_2, CeO_2, and Nd_2O_3 nanomaterials were used as fertilizers for the cultivation of the *P. polyphylla* and *P. trimera*. The SiO_2 application significantly enhanced the growth of aboveground parts, while the CeO_2 and Nd_2O_3 applications prominently improved the rhizome development of the *P. polyphylla* and *P. trimera*. This was because *P. polyphylla* and *P. trimera* absorbed SiO_2 nanoparticles via roots and transferred them to the epidermis walls and vascular bundles of the stem and leaves to create a physicochemical barrier to aid the uprightness and durability of the leaves. The SiO_2 in the plant also improved chlorophyll content, leading to an increase in photosynthetic activity for plant growth. CeO_2 and Nd_2O_3 in the *P. polyphylla* and *P. trimera* provided a medium culture accelerating nutrient uptake of the root to significantly improve its growth.

The study also investigated that ostruthin accumulated in the roots of the *P. trimera* rather than in its stems. In addition, the Nd_2O_3 nanomaterials greatly aided the accumulation of the ostruthin in the roots of the *P. trimera* rather than the SiO_2 nanomaterials. The ostruthin content in the roots of the mixture of Nd_2O_3 and SiO_2 exposed plant was slightly higher than that in the single Nd_2O_3 exposed plant. However, the root weight of the mixture-exposed *P. trimera* was greatly higher than that of the Nd_2O_3-exposed plants. Thus, the use of Nd_2O_3 and SiO_2 mixture still exhibited significant advances for the cultivation of the *P. trimera* as an ostruthin extraction plant.

Finally, the simultaneous use of nano CeO_2 and SiO_2 greatly induced the *P. polyphylla* development. The plant height, stem diameter, leaf area, and rhizome weight under the influence of the mixture of CeO_2 and SiO_2 in *P. polyphylla* were impressively better than those that use the singular nanomaterial as fertilizers. In addition, the CeO_2 nanomaterials significantly supported the buildup process of the gracillin in *P. polyphylla* rhizome rather than the SiO_2 nanomaterials. The combination of CeO_2 and SiO_2 used as fertilizer exhibited significant advances for *P. polyphylla* cultivation to extract the gracillin component.

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TÓM TẮT

ẢNH HƯỞNG CỦA NANO-SiO$_2$, Nd$_2$O$_3$ VÀ CeO$_2$ ĐẾN SỰ SINH TRƯỞNG CỦA CÂY XÁO TAM PHÂN VÀ CÂY BẢY LÁ MỘT HOA

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Nghiên cứu này ứng dụng các vật liệu nano-SiO$_2$, Nd$_2$O$_3$ và CeO$_2$ làm phân bón cho cây Xáo tam phân và cây Bảy lá một hoa. Kết quả thực nghiệm cho thấy việc sử dụng riêng lẻ nano-SiO$_2$, Nd$_2$O$_3$ và CeO$_2$ đã kích thích sự tăng trưởng thân và rễ của cây Xáo tam phân và cây Bảy lá một hoa. Chiều cao cây, chiều dài rễ, trọng lượng thân và rễ của cây được bón với hỗn hợp Nd$_2$O$_3$ và SiO$_2$ hoặc CeO$_2$ và SiO$_2$ cao hơn nhiều so với cây chỉ được bón vật liệu nano riêng lẻ. Các thí nghiệm chiết xuất chỉ ra rằng ostruthin, một dược chất có giá trị, tích tụ chủ yếu trong rễ của cây Xáo tam phân không phải trong thân của nó. Hàm lượng ostruthin trong rễ của Bảy lá một hoa được bón Nd$_2$O$_3$ cũng cao hơn nhiều so với hàm lượng ostruthin trong rễ cây đối chứng và cây được bón SiO$_2$. Hàm lượng gracillin, một dược chất quan trọng, trong thân rễ của cây Bảy lá một hoa được bón CeO$_2$ cũng cao hơn nhiều so với hàm lượng trong cây được bón SiO$_2$.

Từ khóa: Xáo tam phân, Bảy lá một hoa, ostruthin, gracillin, phân bón nano, tác dụng hiệp đồng, nano-SiO$_2$, nano-Nd$_2$O$_3$, nano-CeO$_2$.