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ARTICLE

Agronomic effectiveness of recovered phosphate fertilizer produced from incinerated sewage sludge ash

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Abstract

Phosphorus (P) recovery from incinerated sewage sludge ash (ISSA) has been extensively investigated, but insufficient research has been conducted to evaluate the effect of different kinds of recovered phosphate fertilizers (RPFs) on plant growth with respect to the P and heavy metal contents of RPFs. In this study, three kinds of RPFs, precipitated calcium phosphate fertilizer (CaP), struvite phosphate fertilizer (SP), and P-loaded biochar (BP), produced from ISSA were characterized, and their agronomic effectiveness was verified by hydroponic and soil cultivation. In addition to the three kinds of RPFs, a control group (mono-phosphate fertilizer in hydroponic group/compound fertilizer in soil cultivation group) and a blank control group (BC, with zero P) were tested on choy sum and ryegrass at the same time. SP has the highest P purity (76.0% of struvite) while the BP has the most complex P species (P was co-exist with Fe, Al, and Mg). Plant growth results showed that the RPFs greatly facilitated plant growth and demonstrated superior/comparable effects to those of control group. In hydroponics testing, SP showed the best effect (shoot length of 17.0 cm, chlorophyll content of 2.05 mg/g) due to the Mg involved and the high P purity of SP, while BP performed the best (shoot length of 13.7 cm, chlorophyll content of 2.42 mg/g) in the soil testing system among all of the groups because of the additional nutritional elements and the high P availability of BP. Additionally, the accumulation of heavy metals in the plants under all conditions did not exceed the limits stipulated in the regulations. These results indicate that recovering P from ISSA is an attractive technology to produce P fertilizers, which can alleviate both the scarcity of phosphate resources and the burden of ISSA management.

The original online version of this article was revised to correct the affiliations of author Chi Sun Poon.

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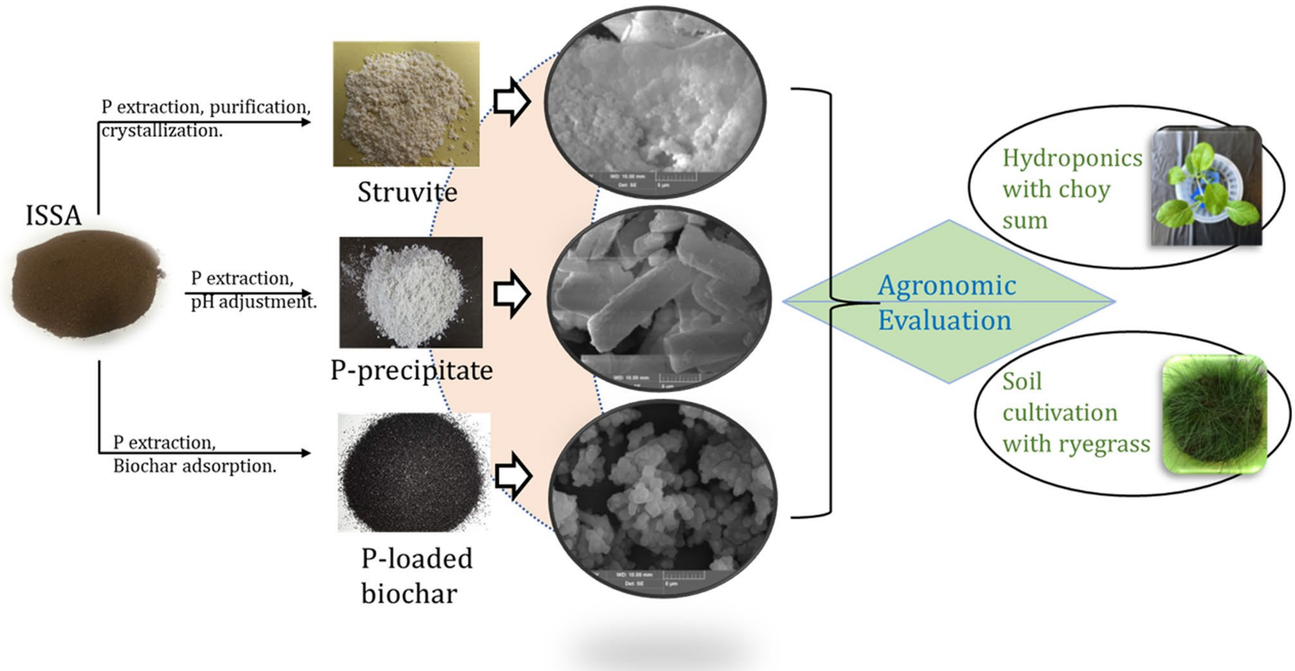
Graphical abstract



Keywords Recovered phosphate fertilizer · Incinerated sewage sludge ash · Agronomic analysis · Heavy metals · Waste management

Abbreviations

BC	Blank control group
BP	P-loaded biochar
CaP	Calcium phosphate fertilizer
CoP	Compound fertilizer
ISSA	Incinerated sewage sludge ash
MP	Mono-phosphate fertilizer
P	Phosphorus
RPFs	Recovered phosphate fertilizers
SP	Struvite phosphate fertilizer

Introduction

Phosphorus (P) is crucial for the growth of plants, and their continual productivity requires the input of P fertilizers. The manufacture of conventional P fertilizer relies on exploiting phosphate rock, the source of which has continued to shrink in recent years [1]. With the decline in the phosphate rock reserve, P fertilizer will not be as economically viable [2–4]. The recovery of P from secondary P sources can not only cater to approximately 22% of the global demand but also optimize the balance of inputs/outputs of P [5, 6].

Various secondary P sources have been explored in P-containing wastes, such as animal manures, wastewater, sewage sludge, and incinerated sewage sludge ash (ISSA) [7–9]. Among these, ISSA is a by-product generated from sewage sludge incineration and exhibits a high P recovery potential [10, 11]. With more countries applying incineration facilities to handle sewage sludge, ISSA is an important waste with a high P content. However, the direct use of ISSA in soil poses threats to the environment due to its high heavy metal contents and poor P bioavailability [12, 13]. Most of studies focused on the P recovery processes, such as P recovery by thermos-chemical method, effect of different sludge conditioners, and P adsorption by different adsorbents, etc. [14–16]. In addition, the P-recovered ISSA can be reused in adsorbing heavy metals, consisting lime-pozzolan and facilitating cement hydration [17–21]. However, the P availability of different recovered phosphate fertilizers (RPFs) for plants and the impact of their heavy metal content on soil or plants have barely been discussed [22, 23]. The plant availability of RPFs is determined by the desorption/release of P caused by flushing and interactions with microbes, soils, and plants [24, 25].

Heavy metals, such as Zn, Cu, Co, and Ni, are essential microelements for plant growth, but their excessive application is toxic [26, 27]. Metals are absorbed by roots and transported in the form of metal complexes or free metals across the root cortex to the stele [28, 29]. Their translocation from RPFs to plants eventually causes them to accumulate through food chains, posing a risk to the health of animals and humans [28, 30, 31]. However, the pros of applying RPFs far outweigh their cons. In addition to alleviating the problem of a finite supply of phosphate rock, RPFs are normally recovered from wastes; thus, the pollution and costs caused by these wastes are reduced significantly. In addition, some RPFs, such as biochar, enhance the water retention effect of soil, mitigate metal pollution, adjust the pH of the soil, etc. [32, 33]. As such, it is difficult to determine the effect of RPFs only through the existing accepted criteria due to their complexity [34, 35]. Hence, plant growth tests are especially important in exploring new kinds of RPFs, which truly reflect their behaviors in soil and their applicability for agricultural production.

Three kinds of phosphate fertilizers (RPFs) can be recovered with three dominant wet-extraction methods of ISSA: adding ammonia gas/liquid to the purified acid extract of ISSA, adding calcium to the purified acid extract of ISSA, and using modified biochar to adsorb P from the acid extract of ISSA [36–39]. These methods produced three kinds of RPFs: struvite phosphate fertilizer (SP) dominantly contains magnesium ammonium phosphate hexahydrate ($NH_4MgPO_4 \cdot 6H_2O$) and is a slow-release fertilizer with high purity [40], calcium phosphate fertilizer (CaP) is a precipitate from the P extract that contains Ca-P and Al-P along with other metals [41], and P-loaded biochar (BP) is a kind of organic matrix that has been shown to enhance the properties of soils [42]. Although the P content of these RPFs has been verified, a systematic study of their agronomic effectiveness is still lacking.

The present study was, therefore, designed to evaluate the agronomic effectiveness of these three RPFs produced from ISSA as sources of P in two different systems for the cultivation of choy sum (*Brassica campestris* L. ssp. *Chinensis var. utillis Tsen et Lee*) and ryegrass (*Lolium perenne* L.). The main objectives of this study were: (1) to characterize the RPFs produced from ISSA; (2) to evaluate the agronomic effectiveness of the RPFs through pot trial tests for the cultivation of choy sum via hydroponics and ryegrass via soil culture experiments; and (3) to analyze the levels of nutrients and the accumulation of heavy metals in the plants.

Materials and methods

Characteristics of RPFs

Three kinds of RPFs were produced from Hong Kong (China) ISSA by different methods, and their detailed production process can be found in the supplementary information (in Supplementary Information, Text S1) [40, 41, 43]. In short, BP was obtained by adsorption of P from acid extraction of ISSA by Mg-dosed sugarcane biochar (700 °C for 1 h with $MgCl_2$ amendment). CaP was precipitated from the P extract by adding $Ca(OH)_2$ to increase the pH of the P extract to 4. SP was produced through struvite crystallization of the P extract prior to purification by cation exchange resin. In addition, the mono-phosphate fertilizer (MP) used in the hydroponic experiment was KH_2PO_4, which is the same as the P sources in Hoagland's solution. The compound fertilizer (CoP) used in soil cultivation experiment was commercial CoP (the purities of N, P_2O_5, and K_2O were 25%, 14%, and 12%, respectively).

For characterization of the RPFs, they were digested using aqua-regia, and then, P and the heavy metal concentrations in the filtrates were measured using a spectrophotometer and inductively coupled plasma/optical emission spectroscopy (ICP-OES, FMX 36, SPECTROBLUE, Kleve, Germany), respectively. The pH of the fertilizers was determined by evaluating the pH of supernatant of 1:20 DI water to fertilizers. The chemical compositions of these three fertilizers are shown in Table 1. The detection limit of metals/heavy metals has been explained in our previous finding [44]. The crystalline phases in the three dried and milled RPFs were analyzed by X-ray diffraction (XRD, Rigaku Smartlab, Tokyo, Japan) using CuKα radiation (λ=1.54059 Å) at 40 kV, and 30 mA was used for scanning. With scanning increments of 0.02° and a counting time of 2 s per step, the peaks were verified in the 2θ range of 10°–70°. The micromorphology of the three RPFs was identified by scanning electromicroscopy with energy dispersive X-ray spectroscopy (SEM–EDX, Hitachi S4800, Tokyo, Japan).

Table 1 pH and contents of SP, CaP and BP

Items	pH	Major elements (g/kg)	Heavy metal (mg/kg)				
			As	Cd	Cu	Pb	Zn
SP	9.5	Mg (62.75), N (52.16), P (63.14), Ca (52.12)	9.3	N.D	26.6	54.7	37.6
CaP	6.5	Ca (251.78), S (130.71), P (61.92), Al (52.19), Fe (16.01)	18.0	19.0	48.0	120.0	136.0
BP	7.2	C (410.1), Mg (42.87), P (30.86), Al (18.12), Ca (17.21), K (3.61)	13.0	10.0	60.5	130.0	215.5

N.D. not detectable, *SP* struvite phosphate fertilizer, *CaP* Calcium phosphate fertilizer, *BP* P-loaded biochar

Pot experiments and determination of the physicochemical characteristics of the plants

Choy sum, one of the major vegetable crops in southern China, was cultivated in hydroponics and nitrites by Hoagland solution/modified Hoagland solution (in Supplementary Information, Table S1) [45]. Ryegrass was cultivated in soil, as it is a fast-growing plant that allows quick P fertilizer efficiency. Hydroponic and soil cultivation were carried out separately as described in the supplementary information (Text S2). The P dose in hydroponic and soil cultivation refers to the Hoagland's nutrient contents, and the P dose is 5.64 gm^{-2} [46]. The soil was sampled from the campus of the southern University of Science and Technology (Shenzhen, China), and the soil cultivation experiment was also conducted here. The chemical properties of the collected soil are shown in the supplementary information (Table S2). Round plastic pots with a diameter of 27 cm and a depth of 20 cm were used. The visual growth conditions of the choy sum/ryegrass were recorded using smartphone cameras. For the choy sum, the number of leaves and the maximum leaf size were recorded on the 7th, 13th, 21st, and 30th days. For the ryegrass, the growth status was recorded at days 30 and 40.

After cultivation, the length (distance from the leaf base to the leaf tip) of the leaf, fresh weight and dry weight (105 °C for 2 h, and 60 °C until constant weight) of the shoot were measured. The chlorophyll contents of the plants were determined using a spectrophotometer after 24 h of extraction of the cut leaf using 95% ethanol [32]. Referring to method of NIST SRM 2711a [47, 48], total digestion was carried out on ball-milled plant samples by using concentrated $HNO_3/HClO_4$ (4:1) on a hot plate, and then the elemental concentrations in the filtrates were analyzed using ICP-OES.

Comparison of the P fractionation of the soils in the different groups

The soils in the five testing groups were sampled, oven-dried and fractionated by a six-step procedure [24]. In step 1, 30 mL DI water was mixed with 1.5 g oven-dried soil for 4 h. After centrifugation (3000 rpm, 5 min) and filtration through a 0.45 μm mixed cellulose ester membrane filter, the supernatant was digested by 10 mL $K_2S_2O_8$ for 1 h, and H_2O-Pt was tested. The P content in the solutions was measured using a spectrophotometer by testing the developed 'molybdenum blue' at 882 nm [49]. Similarly, the residue sludge was tested in step 2 using $NaHCO_3$ to leach out $NaHCO_3$-P. In step 3, NaOH was used to leach out NaOH-P, and then, using HCl to leach out HCl-P in step 4. In step 5, mixed acid (3 M HCl + 6 M H_2SO_4) was used to leach out mix-P, and using concentrated H_2SO_4 and H_2O_2 to digest the residue to measure the residual P in step 6.

Data analysis

Statistical analyses included one-way analysis of variance and Fisher's Least-Significant Difference test. In all cases, a value of $p < 0.05$ was considered to be statistically significant compared to the control group.

Results and discussion

Characteristics of the RPFs

The pH and the contents of SP, CP and BP are presented in Table 1. SP had the highest P content with a value of 63.14 mg/g, followed closely by CaP with a P content of 61.9 mg/g. BP, in contrast, had the lowest P content of 30.8 mg/g. SP had the highest pH of 9.5 of these three kinds of RPFs, while CaP and BP were relatively neutral. SP contains the fewest heavy metals while BP has the most heavy metals, in contrast to these three kinds of RPFs.

As shown in Fig. 1, the crystalline phases of CaP were predominantly $Ca_3(PO_4)_2$ and gypsum, while SP had the highest purity, with a crystalline phase that was only struvite ($Mg(NH_4)(PO_4)\cdot 6H_2O$) [40, 41]. BP had the most complex crystalline phases, which included Al-P ($AlPO_4\cdot 10H_2O$), Mg-P ($MgHPO_4$), and Ca-P ($Ca_{15}(PO_4)_2(SiO_4)_6$) [43]. Figure 2 demonstrates the microstructure of these RPFs. As

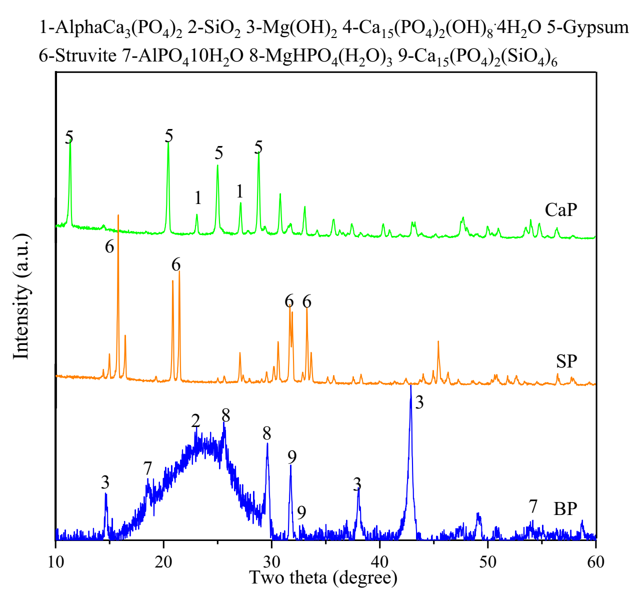


Fig. 1 XRD patterns of three kinds of RPFs. *CaP* Calcium phosphate fertilizer, *SP* struvite phosphate fertilizer, *BP* P-loaded biochar, *XRD* X-ray diffraction, *RPFs* recovered phosphate fertilizers

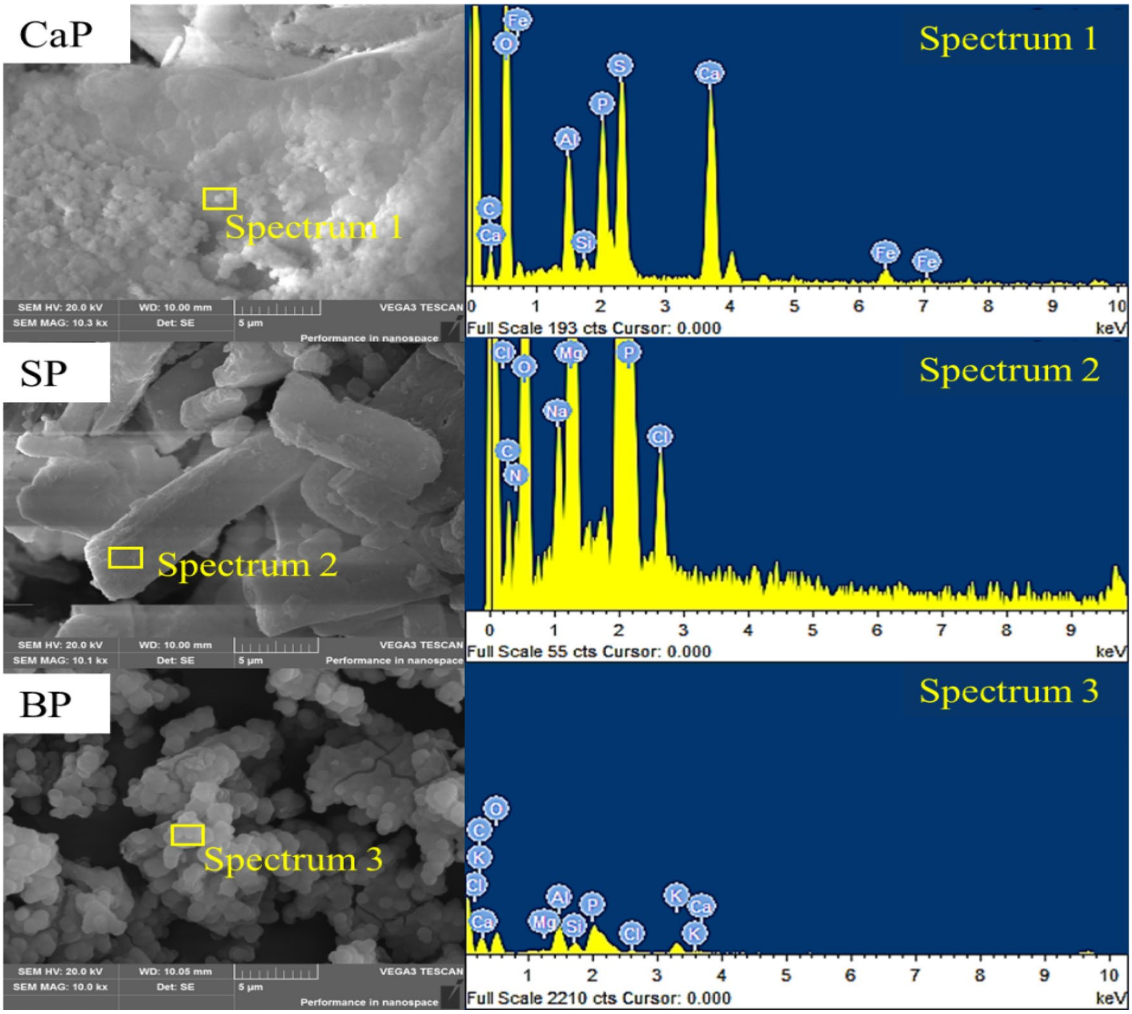


Fig. 2 SEM–EDX analysis of three kinds of RPFs. *CaP* Calcium phosphate fertilizer, *SP* struvite phosphate fertilizer, *BP* P-loaded biochar, *SEM–EDX* scanning electromicroscopy with energy dispersive X-ray spectroscopy

shown, CaP has dense flakes that consist of Fe, Ca, P, and Al; SP has a rod-like surface that consists of Mg, P, and Cl; BP has a loose and porous structure with globular-like precipitates that dominantly consist of Al, Mg, P, and K. Their different crystalline P and microstructure determine their different P effects in soils; for example, the microstructure of BP has the potential to enhance the physical characteristics of the matrix by controlling water flow [50].

In addition, trace elements in nutrients are known to pose a risk of potential accumulation in soils and can be transferred via the food chain [51]. Excessive contents of trace elements in soil or nutrient solutions are essentially toxic to living organisms and growing plants. Table S3 (Supplementary Information) shows the regulation limits of trace elements for fertilizers in different countries [52–55]. The trace elements originated from ISSA, and their major and trace elements can be found in a previous publication [49]. Comparing the values in Table 1 and Table S3, except for CaP, the contents of As, Cd, Cu, Pb, and Zn in BP (13, 10, 60.5, 130, and 215 mg/kg, respectively) and SP (9.3, N.D., 26.6, 54.7, and 37.6 mg/kg, respectively) were within the limits of the fertilizer regulations in many countries. SP has the highest purity among these three RPFs with the lowest level of concerned elements (As, Cd, Cu, Pb, and Zn). In CaP, the content of Cd was slightly higher than the limit, which might be due to the Cd in ISSA that was extracted by acid and re-precipitation during the pH adjustment process [56].

In summary, the total P contents of SP and CaP were similar, and twice that of the BP. CaP has the most trace elements and a dense structure, while SP has the highest purity, and its content is dominantly struvite. BP has the most complex content, but it has the most porous microstructure.

Growth status of the plants

The growth status of choy sum and ryegrass can be found in Fig. S1. For choy sum, the worst growth status was in the BC (control) group, since the leaf number (Fig. S2), size (Fig. S3), and shoot length were the lowest among the different treatment groups. The leaves in the BC group even turned yellow and became seriously withered by the end of the growth period, which suggested that the other four groups were effectively fertilized. In comparison, SP had similar results to the BP group, whose leaf number was 1.8 times that of BC group and whose leaf size was 3.5 times that of BC group. Similarly, the ryegrass in the BC group was paler and thinner than that in the other P fertilization groups and was dark green in color. Additionally, the BP group had the highest germination rate and most developed roots, mostly because biochar increased the soil amelioration effect [57]. The other two kinds of RPFs exhibited germination rates similar to those of the CoP group.

Table 2 Growth indicators of plants

Items	BC	MP/CoP	CaP	SP	BP
Choy sum					
Fresh weight (g/shoot)	0.23b	2.79a	2.49a	2.96a	2.93a
Dry weight (g/shoot)	0.029c	0.16a,b	0.13b	0.18a	0.23a
Shoot length (cm/shoot)	7.2b	15.9a	15.5a	17.0a	16.2a
Chlorophyll contents (mg/g)	1.016	2.04	1.85	2.05	1.83
Leaf number	6	10	9	11	9
Ryegrass					
Fresh weight (mg/shoot)	18.5c	26.6a,b	20.9b	29.2a	21.8b
Dry weight (mg/shoot)	2.6c	3.6a	2.9b,c	3.0b	3.0b
Shoot length (cm)	13.0c	13.4b	13.4b	13.4b	13.7a
Root length (cm)	0.8c	1.2b	1.0b	1.1b	1.5a
Chlorophyll content (mg/g)	1.01d	2.09c	2.15b	2.05c	2.42a

Note: Different lowercase letters mean the results are statically different at $p < 0.05$

To further compare the agronomic effectiveness of the RPFs, the indicators of plant growth, including shoot height and weight, were determined after harvest. From Table 2 and Fig. 3, the average shoot length of the choy sum were significantly increased by 121%, 115%, 136%, and 125% after the application of MP, CaP, SP, and BP compared to BC group, respectively. As shown, the effect of the RPFs was comparable or slightly superior to that of MP in terms of shoot length. No significant differences were observed in the shoot length among the different RPFs used.

For the plant weight, significant differences in the biomass production of the choy sum were found among different treatments with that of the BC. Specifically, the application of BP and SP resulted in the highest fresh and dry weights of choy sum, which were around 11 times those of BC group (Table 2). In contrast, CaP was the least effective among the three RPFs. This might be due to its lower P plant availability compared with the other two RPFs, which included lower P solubility and denser structure. In addition, the high contents of Al (52.9 mg/g) and Cd (19 mg/kg) in CaP would impair the health of the plants [58]. Consistently, the dry weight of the choy sum fertilized with CaP was significantly lower than those fertilized with BP (by 77%) and SP (by 38%). Despite this, the fresh weight and dry weight of the shoots in the

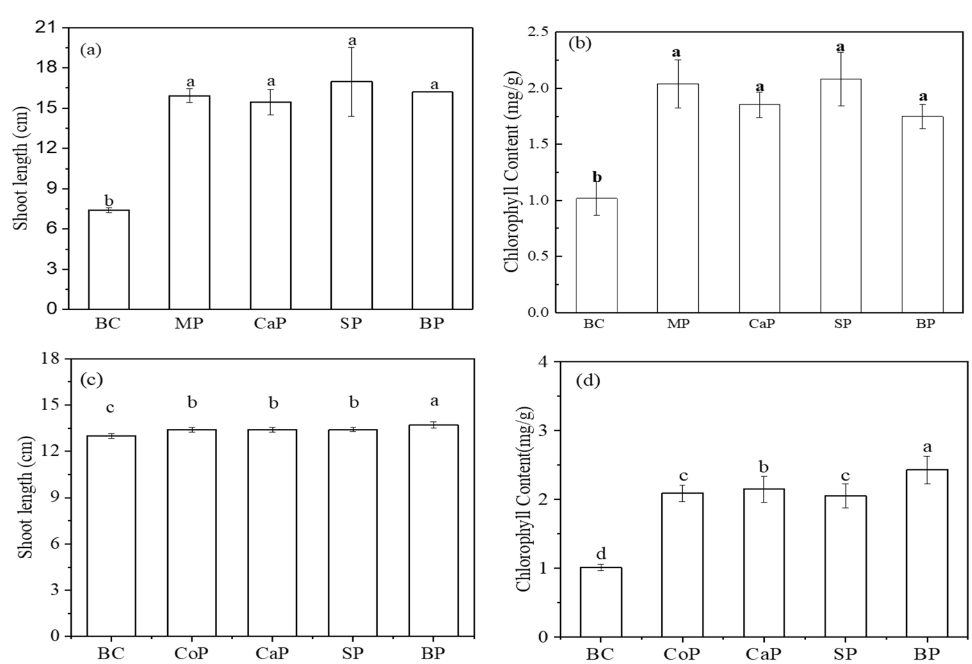


Fig. 3 Shoot lengths and chlorophyll contents of choy sum (**a**, **b**) and ryegrass (**c**, **d**). Letters of a–c means in the same row with different letters differ significantly, significant difference at p < 0.05. *BC* Blank control group, *MP* mono-phosphate fertilizer, *CoP* compound fertilizer

RPF group were significantly higher than those in the BC group. Interestingly, SP produced a higher fresh weight, which might be attributed to the Mg involved and the high bioavailability of SP. Similar results were obtained when struvite was applied to cultivate lettuce, which was attributed to the high amount of Mg incorporated into struvite and its synergistic effect on P uptake [59]. Magnesium is an essential component of the chlorophyll molecule; thus, it plays a critical role in photosynthesis [59]. This could be reflected in Fig. 3b, since SP produced the highest chlorophyll content, confirming that Mg played a significant role in photosynthesis by the plant.

In the case of ryegrass, BP pots had the highest shoot length, with an average value of 13.7 cm, closely followed by CoP, SP, and CaP pots which had similar values (13.4 cm). As expected, the ryegrass in the control group had the shortest average shoot length (13.0 cm) due to its lack of P. In addition, the root system of the BP group was obviously better developed and was longer than that of the other groups, while the BC group had the shortest and worse developed roots. The fresh weight of the plants followed the order SP > CoP > BP > CaP > BC. Specifically, the fresh weight of the SP group was 29.2 mg, which was 25% and 36% higher than those of BP and BC, respectively. As expected, ryegrass in the SP group had the highest chlorophyll content. It should be noted that due to the relatively small amount of ryegrass after harvest, the dried masses of all pots were all low and similar.

Overall, SP containing a high content of Mg was beneficial for the photosynthesis of chlorophyll, thus promoting the growth of plants. BP also stimulated the growth of plants (especially for the root systems) due to its highly porous structure and the additional nutrient elements in the biochar. The agronomic effectiveness of BP and SP were comparable to or even better than that of CoP as a P source for the cultivation of ryegrass. The agronomic effectiveness of CaP was slightly lower than that of CoP but significantly better than that of the BC group. Even though it is inferior to other P fertilizers, CaP could still be regarded as a potential P source due to its growth-promoting effect on ryegrass.

P release from RPFs and uptake by plants

In contrast to soil, hydroponics testing in which P is released only through dissolution, RPFs/P fertilizers in soil cultivation release P through dissolution and reactions with plant roots and microorganisms. Under the same abiotic and biotic factors, the soil P levels can reflect the transformation of different RPF fertilization schemes [60].

Figure 4 shows the P contents and fractions in soils in different groups. As expected, the total P of the BC group was the lowest, and the other 4 P fertilization groups had similar total P contents. The non-labile P in CaP and SP was similar, while the labile P in SP and BP were similar. Considering the growth of plants, the development of plants was dominantly determined by labile P. Furthermore, BP had the thickest plant growth, and the $NaHCO_3$-P of BP was the most abundant among four groups. The CaP group had the lowest labile P among the four P-fertilized groups, which can be explained by its dense structure, and $Ca_3(PO_4)_2$ had low plant availability, as alluded to in the Section "Characteristics of the RPFs". In addition, the residual P of BP was the lowest among these four fertilized groups, while the CoP was the highest. All results indicated that the three kinds of RPFs had comparable P effects relative to CoP. BP had the highest P availability with more labile P and the least residual P.

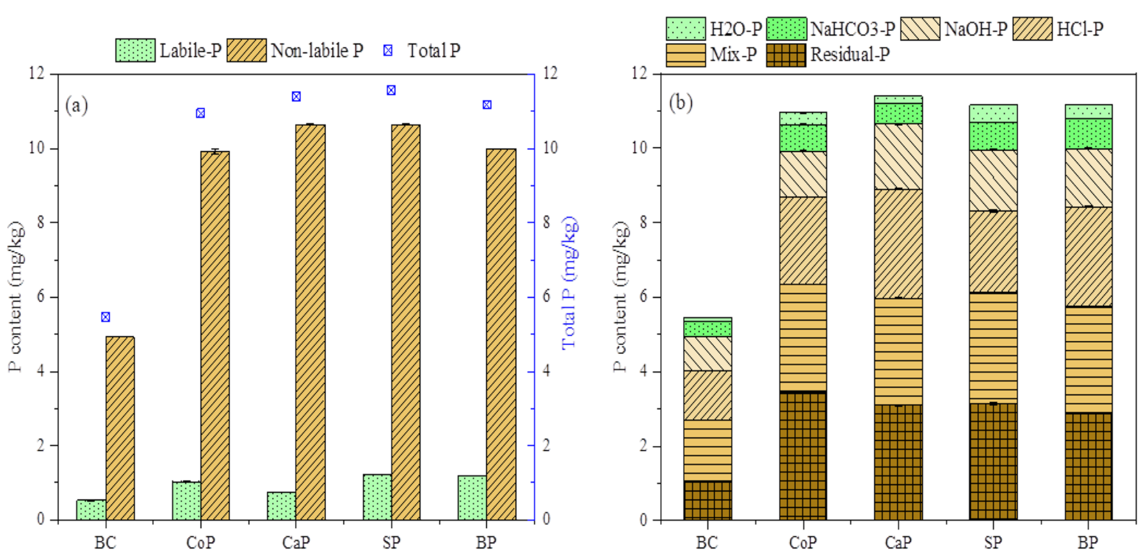


Fig. 4 The P contents and P fractions of soils in different groups: (**a**) the labile-P, non-labile, and total P content of soils; (**b**) the P fractions of soils

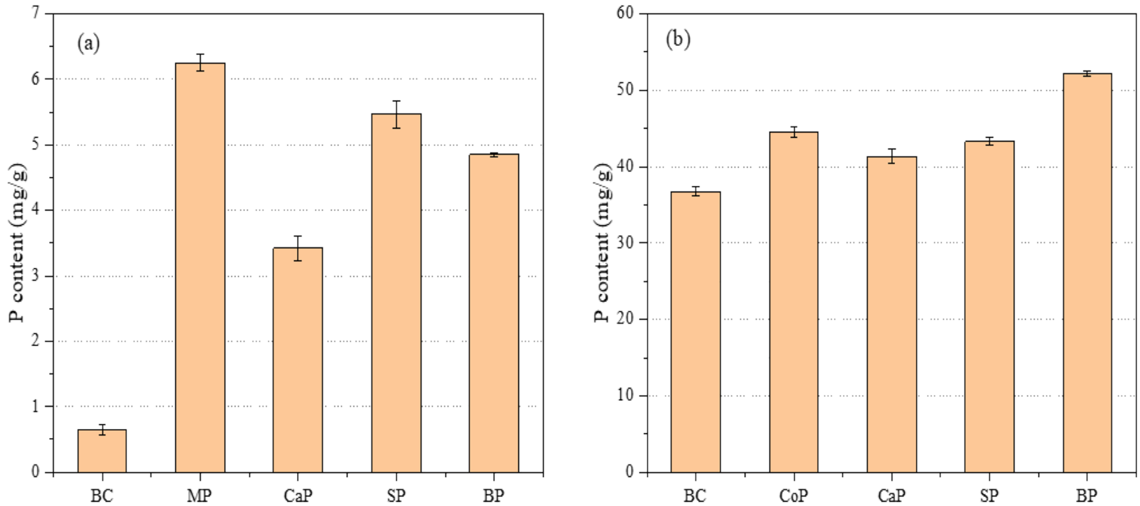


Fig. 5 P contents of plants: (**a**) choy sum shoot; (**b**) ryegrass

Figure 5a shows the P content in choy sum shoots after harvest using different P sources. The BC pots undoubtedly had the lowest P content due to the lack of P sources. The MP pots had the highest P content with a value of 6.25 mg/kg, mostly due to the high P solubility of MP. SP and BP had similar P contents of 5.32 mg/kg and 4.76 mg/kg, respectively. The CaP pots only had 3.33 mg/kg. Figure 5b shows the P content in ryegrass. The difference between BC group and fertilized group was not as large as those in hydroponics because there are also some available soils. The P concentration in CaP was the lowest of the fertilized groups, which was attributed to its dense structure, and the lowest total P and labile P of CaP compared with SP, BP, and MP. The highest P concentration in BP group was not only due to the high labile P of BP but also because of the porous and high surface area of BP, which provides more sites for contacting microorganisms [61]. In particularly, the roots of ryegrass in BP group were the most developed of all study groups, with many lateral roots. This may be because biochar can not only provide essential elements for plants but also its high porosity can retain water and promote growth of microorganisms [62].

In summary, the development of choy sum in hydroponic is more determined by the dissolution of fertilizers. The RPFs have comparable P effects with commercial fertilizer, which demonstrated their acceptable P availability, especially SP and BP.

Heavy metal accumulation in plants and soils

The metal contents in the choy sum shoots and ryegrass were determined and shown in Fig. 6. The released P (PO_4^{3-}), nitrogen (NH_4^+) and magnesium (Mg^{2+}) can be adsorbed simultaneously by plants along with any released metals. The detected metals were different between the two kinds of plants due to their different growing environment and growth characteristics. The metal content in the dried choy sum shoot (Fig. 6a) followed the order of Zn > Cu > Cd > Pb > Co ≈ As in different treatment groups. The As contents in all fertilized plants were similar and

Fig. 6 Uptake of heavy metals by plants: (**a**) choy sum shoot; (**b**) ryegrass

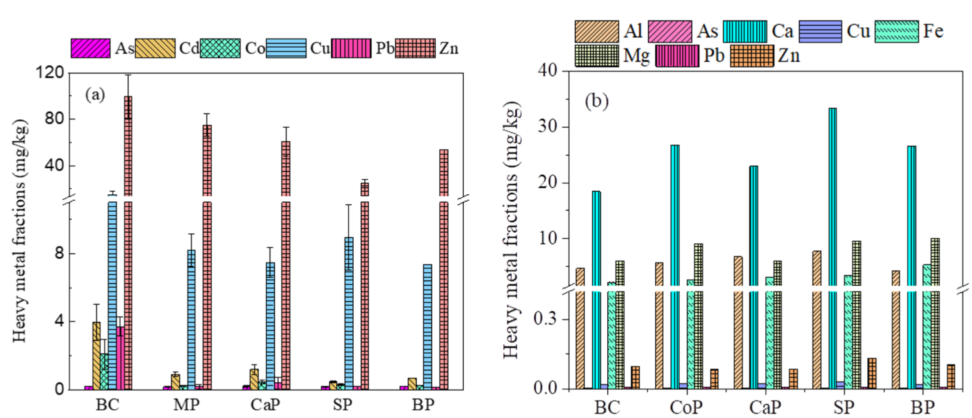


Table 3 Ranges and safe limits of heavy metals in *Brassica* vegetable family cultivated using RPFs (mg/kg dry weight)

Items	Ryu et al. [64]	Ryu et al. [63]	This study	Safe limits		
				SFDA [67]	Tasrina et al. [65]	FAO [66]
Zn	121.0	68.0	24.98–60.73		60	
Cu	7.2	20.5	7.38–8.94		40	
Co			0.27–0.45		0.05–0.1	
As	n.d	n.d	0.19–0.22	0.5	0.2	
Cd	n.d	n.d	0.47–1.20	0.05–0.2	0.3	0.02–0.2
Pb	n.d	4.5	0.13–0.40	0.1–0.3	0.2–0.3	0.05–0.3

n.d. not detected

within the range of 0.19–0.23 mg/kg. Similarly, the Co contents were comparable within the range of 0.25–0.45. The Cd and Cu contents in the fertilized plants were also comparable. Specifically, both the SP and BP fertilized plants had lower Cd contents than that in MP plants, and the CaP fertilized plants had the highest Cd content. For Cu, the CaP and BP groups had relatively lower contents than the SP and MP groups. In contrast, significant differences were observed for the Zn contents in the different groups. The MP fertilized plants had the highest Zn content with an average value of 75.05 mg/kg, followed by CaP, BP, and SP. The Zn content in the SP plants was 24.98 mg/kg, which was significantly lower than that in the other groups. These results indicated that the contents of heavy metals in choy sum met the limits regulated by the FAO/WHO and several other countries (Table 3) [63–67]. This finding reveals that the utilization of these RPFs to cultivate choy sum does not endanger human health through heavy metal accumulation in plants. In summary, the comparable or even lower heavy metal contents in the RPF fertilized plants indicated that they could be safe for choy sum cultivation.

The uptake of various metals by ryegrasses is shown in Fig. 6b. No obvious differences were found in heavy metal contents among the three kinds of RPFs along with the CoP and BC cultivated ryegrass. This might be due to the trace amounts of heavy metals in the natural soils and the low plant availability for the metals in the fertilizers. The relatively lower heavy metal contents found in the BP group might be attributed to its porous structure with a high adsorption capacity for heavy metals [61]. In particular, the Al content of the BP group was the lowest because the organic compounds of BP can decrease the Al content [50]. Although these three kinds of RPFs contained higher contents of metals, no obvious increase in the metal contents was found in their cultivated plants, such as Zn, Fe, Mg, etc.

For animal feed, only As (<4 mg/kg), Cd (<1 mg/kg), and Pb (<30 mg/kg) are regulated as the maximum allowable concentration in ryegrass with a moisture content of 12% [68, 69]. However, in this study, the maximum contents of these elements were As (2.8 mg/kg), Pb (7.8 mg/kg), and Cd (below the detection limit), which are much lower than the limits stipulated in the regulations.

Conclusions

Recovering P as fertilizer from ISSA not only sustains the global P cycle but is also beneficial to ISSA management. The three studied RPFs are three kinds of representative products recovered from ISSA through wet-extraction methods, which contained significant amounts of P (SP, CaP, and BP were 63.14, 61.92, and 30.86 g/kg, respectively). This study demonstrated that RPFs produced from ISSA exhibited comparable/better agronomic effectiveness for the growth of choy sum and ryegrass than commercial MP/CoP due to their similar P effects in soils. BP significantly enhanced the shoot length (13.7 cm), root length (1.5 cm), and chlorophyll content (2.42 mg/g) of ryegrasses in soil cultivation due to its high labile P and porous structure; struvite effectively facilitated the fresh weight (2.96 g/shoot), shoot length (17 cm/shoot), and chlorophyll content (2.05 mg/g) of choy sum in a hydroponic environment due to its high purity. Negligible/no heavy metal contamination was found in the cultivated plants, indicating a low risk of using RPFs from ISSA. In general, recovering P as struvite or adsorbing P from the acid extract of ISSA using biochar are preferred options for producing fertilizers from ISSA. Due to the different pH values and physical characteristics of these two kinds of RPFs, their effects on the soil profile in long-term processes still need further study.

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Declarations

Conflict of interest The authors of this manuscript have no conflicts of interested related to the content of the study.

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