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REVIEW

Phosphorus supply and management in vegetable production systems in China

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Abstract Vegetable production systems involve high rates of chemical and organic fertilizer applications, leading to significant P accumulation in vegetable soils, as well as a decrease in P use efficiency (PUE), which is one of the key limiting factors in vegetable production. This review introduces the vegetable production systems in China and their fertilization status, and analyzes probable causes of overfertilization of vegetable fields. Poorly developed root systems and high P demand have led to the need to maintain much higher available P concentrations in the root zone for regular growth of vegetables, which might necessitate higher phosphate fertilizer input than the plants require. Research on strategies to improve vegetable PUE and the mechanisms of these strategies are summarized in this review. Increasing the P uptake by vegetables by supplying P during the critical growth stage and effectively utilizing the accumulated P by optimizing the C:P ratio in soils can substantially increase PUE. These advances will provide a basis for improving PUE and optimizing phosphate fertilizer applications in vegetable production through regulatory measures. In addition, some policies are recommended that could ensure the safety of vegetables and improve product quality. This review also aims to improve understanding of P cycling in vegetable fields and assist in the development of best practices to manage P reserves globally.

Keywords phosphate fertilizer, phosphorus use efficiency, vegetable production systems, phosphorus management, policy recommendation

1 Introduction

Vegetables, as major economic crops, are an important component of the human diet, as vegetable contain many kinds of fiber, carbohydrates, vitamins and minerals[1]. With the change in the Chinese dietary practices, the consumption of vegetables has rapidly grown in China. An estimation of consumption data shows that annual vegetable consumption in China was about 96 kg per capita in 2017[2], while total demand for vegetables is predicted to reach 5.9 Mt by 2020 according to the National Vegetable Industry Development Plan (2011–2020)[3]. Therefore, vegetable production is increasing in China to meet the demand and provide more vegetables to society. The total area of vegetable production in China was about 20 Mha in 2017, which was five times higher than in 1978[2]. Over the past two decades in China, many rice-wheat rotation fields have been converted to greenhouse production systems in response to the growing demand for vegetables[4].

Vegetable cultivation as an intensive production system is characterized by high inputs and high yields. Vegetable growers routinely apply excessive fertilizers with the intention of increasing profits, with P application rates exceeding P removal in harvested fields by several fold[5]. Moreover, vegetables receive a higher P input than cereal crops. Based on data for 13 Chinese provinces from 151 studies published from 1990 to 2018, the amount of phosphate fertilizer applied was about 541.4 $\mathrm{kg \cdot ha^{-1} \cdot yr^{-1}}$ for vegetables, which was more than four times that applied to cereal crops[6]. However, this practice of phosphate fertilizer application is based on yield goals and it does not consider actual nutritional requirements in vegetable production systems, which has resulted in the accumulation of residual P and lower P use efficiency (PUE) in vegetable soils. Khai et al.[7] reported that the surplus of P ranged from 109 to 196 $\mathrm{kg \cdot ha^{-1} \cdot yr^{-1}}$ in small-scale vegetable farming systems in South East Asia. The concentration of P in vegetable soils was several times higher than that in cultivated soil in northern China[8]. Moreover, vegetable production systems involving a high amount of phosphate fertilizer application can lead to significant P losses to the environment, resulting in water body eutrophication. According to a national-level

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analysis, the annual total P (TP) load from open-field vegetable systems in China was 0.33 Mt via runoff[6]. Excessive input of P has also led to land degradation in many areas in China. Therefore, there is an urgent need to develop sustainable vegetable production strategies.

In some vegetable production regions, there have been many studies on P availability and management, especially in terms of vegetable PUE, C:P ratio and threshold values of P losses in vegetable soils. This review provides an overview of the current status of development in vegetable production systems in China, discusses the possible reasons for overfertilization, introduces approaches to increase the PUE of vegetables and finally proposes some policy recommendations that should be helpful for sustainable development of vegetable production (Fig. 1).

2 Current development status of vegetable production systems

2.1 Status of vegetable cultivation

Vegetable production systems can be classified into two types: open field systems and greenhouse systems. Open-field vegetables are grown in rotation, typically with two or three crops according to the soil fertility and climate in local production systems. Unlike open-field systems, greenhouse production systems, with special climate conditions and management practices, prolong the growing seasons to produce many kinds of vegetables all year round[9]. This type of cultivation practice has rapidly expanded around the world over the last few decades[10–12]. Greenhouse production is particularly widespread in Turkey, representing 96% of total production[13]. In China, greenhouse vegetable production was less than 15000 ha in 1983 and has expanded to nearly 4.7 Mha in 2010[14,15]. Compared with the greenhouse vegetable production in other regions of China, in eastern China with the majority of China's arable land, the area of greenhouse production is much greater, with 22.6% in Liaoning, 14.2% in Shandong, 10.9% in Jiangsu and 10.4% in Hebei, in 2013[16,17].

Greenhouse vegetable production systems in China can be classified into two types in terms of fertilization practices, standard and organic, with the latter using organic fertilizers and no pesticides or growth regulators[18,19]. In recent years, organic vegetables have become increasingly popular among consumers because they are free from pesticide residues, and organic vegetables are considered healthy for humans[20]. For growers, the attraction of growing organic produce is that it usually attracts a 10%–30% price premium in the market[21]. Greenhouse vegetable production systems in China generally follow one of two models of management,

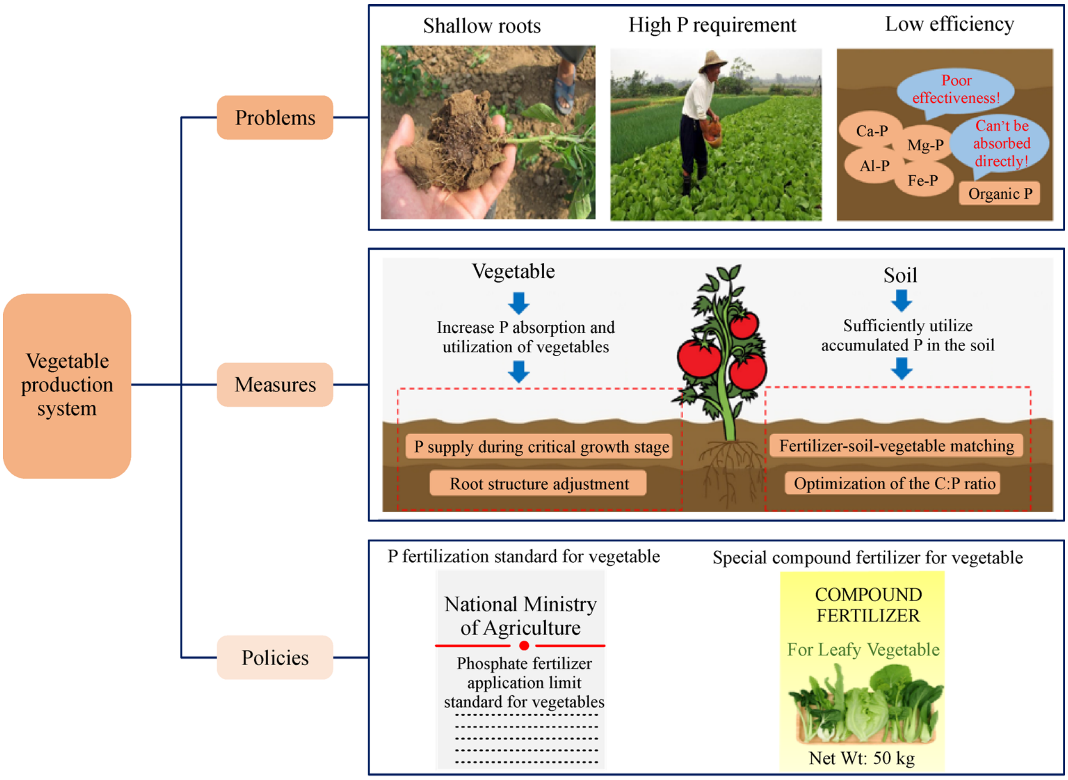

Fig. 1 Schema outlining the causes of overfertilization, approaches to increase PUE and policy recommendation in vegetable production systems.

household or enterprise management[22]. In the family model, management decisions and profits belong exclusively to farmers. Whereas, in the enterprise model, management decisions and profits belong to the management teams, and farmers are generally hired as salaried employees[23].

2.2 Status of phosphate fertilizer application in vegetable fields

The relatively high economic value of vegetables has prompted farmers to apply large amounts of fertilizers to obtain maximum yields. Vegetables are the main crops for the application of phosphate fertilizer in China, while the proportion of phosphate fertilizer consumption in vegetables has shown an upward trend compared to wheat and rice and the amount of P applied to vegetables is approximately 1.7 × 10^6 t P_2O_5 in 2017[24] (Fig. 2). Survey results indicate that the majority of farmers (65%) prefer to use a combination of organic manure and chemical fertilizers in vegetable production systems in China[23,25]. Furthermore, horticultural practices have involved using more organic fertilizers, such as pig and chicken manure, and sewage sludge, especially in greenhouses. Based on data for 16 Chinese provinces from 28 studies published from 2003 to 2009, the proportion of organic phosphate fertilizers applied in greenhouse vegetable production systems was 21.5%–65.4%, while in open field, organic phosphate fertilizer accounted for 26.5%–48.2%[26] (Fig. 3). These studies showed that livestock manure was used as the basal fertilizer, being uniformly broadcast and incorporated into the topsoil before each crop. In contrast, the chemical fertilizers were generally applied as both basal and topdressed fertilizers[14].

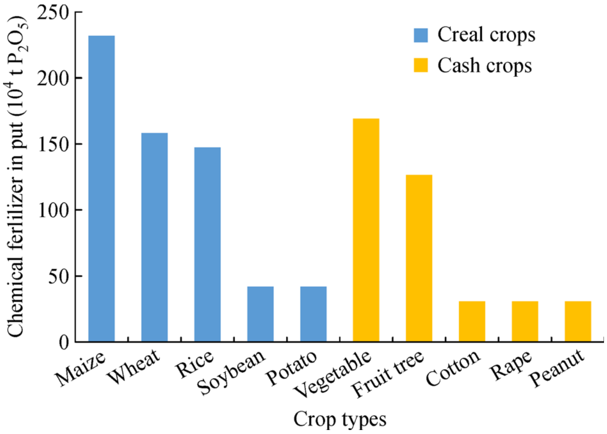

Fig. 2 Total chemical P application rate of different crops in China during 2017 (calculated from Wang[24]).

Generally, the N:P ratio of manure (2:1) is lower than that needed for vegetable uptake (4:1–12:1)[27], so continuous applications of manure based on the N requirements will lead to excessive P input and a large P accumulation resulting in a high risk of P losses to the environment[28]. Although contrary to these data, some scholars argue that organic farming represents an environmentally-friendly system[29], while high-external input agriculture is not[30]. Large quantities of livestock manure or compost, as a complete substitute for chemical fertilizers, have been a main source of nutrients to fertilize vegetable soils in most organic vegetable production systems. For example, about 2–20 t·ha^{-1} composted animal manure was applied annually in organic vegetable cultivation in Nanjing, China[31].

2.3 Characteristics of the phosphorus pool in vegetable soils

To achieve a high level of economic benefits, long-term repeated application of phosphate fertilizer based on farmer experience rather than on soil analysis and vegetable requirements has resulted in excessive accumulation of P in vegetable soils. Soil Olsen-P is an important index to indicate the soil P supply capacity and evaluate the risk of soil P losses to the surrounding environment[32]. An investigation was conducted to determine the soil P status in greenhouse vegetables, the results showed that the concentrations of Olsen-P varied significantly in different areas, with a mean of 153 mg·kg^{-1} and the soil P content reached 328 mg·kg^{-1} in Xinjiang County in southern Shanxi Province[33]. Compared with open-field vegetable production, greenhouse vegetable production provides continuous production all year round with high-intensity inputs and high cropping indexes[34]. Therefore, the additive effect of P occur more clearly in greenhouse soils than in open-field soils. The mean concentrations of TP, Olsen-P, inorganic P (P_i), and organic P (P_o) were higher in greenhouse vegetable soils than in open-field soils. Liu et al.[35] reported that most studies on available P found higher concentrations in greenhouse soils than in open fields. For example, in Shouguang, Shandong Province, available P averaged 225 mg·kg^{-1} in surface soil (0–20 cm) in greenhouses and was over 10 times higher than in open fields. Also, concentrations of different P fractions, such as Olsen-P, Ca-P, Al-P and Fe-P, were higher in the surface soils than the subsoil, and the concentrations decreased significantly with increasing soil depth[36]. In addition, the concentrations of P in vegetable soils increased with increasing years of production. Li & Zhang[37] surveyed vegetable topsoil in northern Zhejiang Province and found that TP and Olsen-P were positively correlated with years of production. The concentrations of TP and Olsen-P in vegetable soil after 30 years of production were about 3.2 and 7.7 times higher, respectively, than those in vegetable soil with less than 2 years of production.

Generally, much higher levels of different P fractions were observed in vegetable soils than in grain fields due to

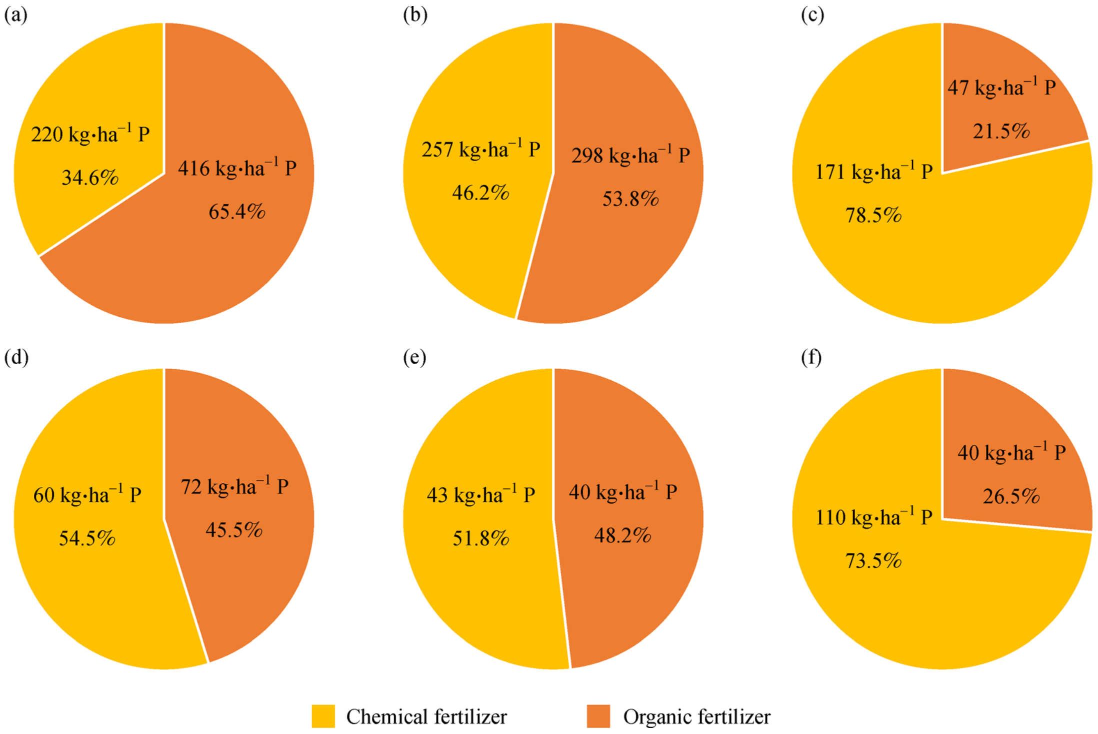

Fig. 3 Proportion of organic and chemical phosphate fertilizers applied in vegetable production systems in China. (a) Fruit vegetables in greenhouse; (b) melons/squashes in greenhouse; (c) leafy vegetables in greenhouse; (d) leafy vegetables in open field; (e) root vegetables in open field; (f) alliums and ginger in open field. (Calculated from Yan et al.[26].)

the increasing amounts of fertilizer used by farmers in vegetable production[38]. For example, the concentration of Olsen-P in vegetable soils was 48.8 mg·kg^{-1} in the topsoil (0–20 cm), which was twice as much as that in adjacent grain fields in Hebei, China[39]. According to a survey of 34 farm soils in Sydney, Australia, the soils used for vegetable production had extremely high concentrations of TP and $CaCl_2$-P with means of 1205 and 4.3 mg·kg^{-1}, respectively, in the 0–30 cm soil layer, and the concentrations of $CaCl_2$-P in fertilized soils were as much as 230 times greater than similar but unfertilized reference soils[40].

3 Analysis of the causes of overfertilization in vegetable fields

3.1 Vegetable roots with shallow morphological characteristics

The diffusion of P to the root is the major way that vegetables absorb P, and vegetable roots are characteristically shallow. Furthermore, P is easily fixed by Fe, Al and Ca in soils[41], and making it largely unavailable for plant uptake. Since vegetables take up P at a much higher rate than P diffuses within the root-zone soil, a P depletion zone is quickly established[42]. Therefore, there is spatial dislocation between vegetable root P demand and P supply in the root-zone soil.

3.2 High phosphorus requirement of vegetable crops

Plant species differ widely in terms of PUE. In comparison to cereal crops, vegetables have a much higher P demand throughout their growth period. To reach 80% of their maximum yield, in comparison to wheat, vegetables, such as onion and tomato, require a much higher P concentration in the soil, and low uptake efficiencies of onion and tomato were associated with a low root-shoot ratio and a low influx rate[43]. For example, application of phosphate fertilizer still significantly increased amaranth yield at an Olsen-P level of 74.2 mg·kg^{-1}[44]. In a soil containing an Olsen-P level of 54 mg·kg^{-1}, lettuce yield significantly increased with the application of phosphate fertilizer[45]. However, rice yields show no increased response to phosphate fertilizer application when soil Olsen-P is over 21.3 mg·kg^{-1}[46].

4 Efficient utilization of phosphorus by vegetable crops

4.1 Increased phosphorus absorption and utilization

4.1.1 Phosphorus supply during the critical growth stage

Kinetic parameters, such as maximal uptake rate (V_{max}), are very important characteristics for P acquisition. P uptake parameters change continuously with the growth of plants[47–49], indicating that P uptake efficiency varies between different growth stages. Liang et al.[50] found that during cucumber growth V_{max} decreased, with the highest value in the initial growth stage. This result means that the P absorption of cucumber plants was more efficient and critical at the seedling stage that at other stages.

Qi[51] found that although P application in seedling soil and in the transplantation periods both significantly promoted cucumber growth, the application in seedling soil was more effective with a significant positive correlation with plant biomass. From 0 to 240 $mg \cdot kg^{-1}$ P applied in the seedling stage, significant improvements were found in dry weight, and the effect of increasing biomass reached 100 $mg \cdot kg^{-1}$ P. Therefore, optimum available P in the seedling stage of cucumber can maximize crop yields.

4.1.2 Root density and architecture adjustment

The root system, as the main interface between the plant and its surrounding soil environment, is important for nutrient and water uptake and storage[52]. The plasticity of root morphology is the key characteristic that ensures plants survive in continuously changing environmental conditions[53]. For example, root system architecture could be greatly altered upon phosphate depletion, leading to a shallower root system bearing more and longer lateral roots as well as denser root hairs[54]. Generally, larger root systems with larger root-surface area, longer root hairs, and greater density of root hairs are closely associated with greater P uptake efficiency when the soil P concentration is low[55]. Therefore, the adaptation of root morphology is particularly relevant for vegetables when competing for the acquisition of immobile ions such as P_i[56]. Studies have shown that aeration irrigation could significantly promote the growth and activity of vegetable roots. Oxygation (aerating the rhizosphere via the irrigation stream) promotes shallow-rooted crops, such as soybean, to grow to a greater soil depth, as observed by the general increase in root weight and root length density. The effect of oxygation on the yield of shallow-rooted crop vegetables increased yield by 43%[57]. Furthermore, in comparison to non-aerated irrigation, aerated irrigation had significant effects on cucumber growth in a greenhouse in terms of PUE, and root activity increased by 2.4%–66%[58].

4.2 Sufficient utilization of the accumulated phosphorus in soils

4.2.1 Optimization of the C:P ratio

A large amount of applied manure has led to a decrease in soil C:P ratios, and these ratios in greenhouse soil range from 5.8 to 9.0, which is lower than those in field soil (9.1–10.2)[59]. The lower PUE might be due to the imbalance between C and P and might also lead to a lower P_o mineralization rate[60]. The process of soil P_o turnover depends on soil microbes (especially soil P-solubilizing bacteria) and soil phosphatase activity, which are closely related to soil management practices[61]. Biochar, a soil amendment, has emerged as an attractive option to increase C:P ratio. With unique physical and chemical properties, biochar has been confirmed to have positive effects on P availability and reducing P losses in soils by changing the process of P adsorption and desorption[62]. Biochar can also have an important role in soil P transformations in vegetable soils. Recent studies have indicated that biochar increases $NaHCO_3$ extractable P and resin P, which are considered the most available for plant growth; soil available P content is also elevated[63]. Moreover, biochar contains a large amount of P, thus, direct release of soluble P may be necessary to enhance P availability, especially for short-term use[64].

4.2.2 Fertilizer-soil-vegetable matching

P uptake depends on not only the amount of available P in soil but also vegetable species and soil types. Some scholars found that in acidic soils, radish had a greater ability to absorb Al-P than Ca-P, whereas in calcareous soils, rape uses Ca-P more efficiently than Al-P[65]. Different vegetable species have significant variation in their use of different forms of inorganic phosphate; lettuce and spinach have high utilization of Ca-P, while in tomato utilization of Al-P is higher[66]. Therefore, sufficient utilization of accumulated P in vegetable soils could be achieved by some horticultural measures, such as rational rotation or continuous cropping. In comparison to other measures, a pak choi-amaranth rotation uses the P in P-enriched soils better; results from pak choi-amaranth rotation experiments indicated that soil available P content and soil water-extractable P content decreased when the yields of pak choi and amaranth increased[67].

Also, fertilizer-soil matching is important to increase the PUE of vegetables. A large proportion of TP is unavailable to vegetables in calcareous soil due to the rapid fixation of P. Some scholars have found that in comparison to granular phosphate fertilizer, liquid phosphate fertilizer had significantly higher availability, mobility and solubility in calcareous soil and could significantly promote the absorption of P by plants[68]. Chu et al.[69] found that in comparison to the granular P application, liquid fertilizer application significantly reduced soil P fixation and increased Ca_2-P and Ca_8-P; hence, liquid fertilizer improved PUE by 5%–15.5%, and the yield of tomato increased by 18%–51%. Therefore, regulatory measures that involve fertilizer-soil-vegetable matching and technical integration would be effective for increasing vegetable PUE.

5 Policy recommendation

5.1 Proposed drafting of a limit standard for P application to vegetable soil

We have listed some measures to use P efficiently above, such as adjusting root structure and supplying P during the critical growth stage. Further scientific research could be strengthened by focusing on the relationship between different types of vegetables and soil nutrient status, such as, ensuring that the critical concentrations of Olsen-P for different vegetable species exist in root-zone soil without yield reductions. Another research focus could be whether the soil Olsen-P concentration threshold could be effectively reduced by technologies that improve efficiency. When scientific research has established make sure the optimum fertilization amount, the government, as a management entity, should propose management strategies that include drafting a limit standard for chemical-P-fertilizer application and develop guidance for vegetable production systems based on comprehensively considering local nutrient status and different vegetable P demands. The government could encourage farmers to follow the rules by paying a targeted subsidy.

5.2 Producing special compound fertilizers for vegetables

Farmers prefer to use compound fertilizers in vegetable production systems in China due to the convenience and labor savings associated with them. Generally, the N:P:K ratio of composite fertilizer of 1:1:1 is different from the uptake and demand ratio (1:0.3:1.4). This imbalance in the N:P:K ratio is common in vegetable production systems. The data shows that the application of P is excessive, while the inputs of N and K are low[27]. Over-application of P can, to some extent, increase the content of soluble sugar, vitamin C and soluble solids[70]. Whereas, P-deficiency can cause stunted and short tomato plants, which seriously affects the yield and quality[71]. With living standards improving, people are becoming increasingly concerned about vegetable quality and safety. It is important to determine how to ensure the safety of vegetables and improve quality and safety standards, which are not only of interest to the public but also important for improving the competitiveness of the vegetable industry. Therefore, fertilizer producers should be encouraged to produce suitable N:P:K ratios of compound fertilizers based on vegetables nutrient requirements. Vegetable fields, as special production systems, use amount of organic manures or composts as base fertilizer. Thus, the ratio N:P:K of special compound fertilizers should subtract the amount of N, P, and K from organic fertilizer according to the local-fertilization habit. This approach could effectively address the problem of unsustainable P application caused by fertilizing based on N demand and could also improve vegetable quality. At the same time, the government should accelerate the construction of a new agricultural subsidy policy system, for example by setting a minimum purchase price policy for good-quality vegetables to ensure farmer profits.

China’s agriculture has undergone the policy change “zero growth of chemical fertilizer use” to “fertilizer reductions, quality improvements and efficiency increases” proposed by Ministry of Agriculture of the People’s Republic of China, which identify the greatest challenges for agricultural production systems. Therefore, strengthening the regulation of vegetable quality by P management in vegetable production systems is a developing trend for the future.

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