Reduction of Phosphatic and Potash Fertilizer in Sweet Corn Production by Pre-transplanting Application of Potassium Phosphate to Plug Seedlings

Kazuhiro Watanabe1, Tohru Murayama2, Takao Niino3, Tsuneo Nitta2 and Masami Nanzyo4

1National Agricultural Research Center, NARO, Tsukuba, Ibaraki 305-8666, Japan; 2National Agricultural Research Center for Tohoku Region, NARO, Fukushima, Fukushima 960-2156, Japan; 3National Institute of Agrobiological Sciences, Tsukuba, Ibaraki 305-8602, Japan; 4Faculty of Agriculture, Tohoku University, Aoba-ku, Sendai, Miyagi 981-8555, Japan

Abstract: To develop a new fertilizing system with a reduced amount of phosphatic fertilizer in sweet corn production, we applied potassium phosphate to the plug seedlings before transplanting to the field, and examined its effects on growth, yield, photosynthetic activity and absorption of minerals. The amount of phosphatic and potash fertilizers necessary to grow sweet corn could be reduced by the pre-transplanting KP application (PTKPA) to the plug seedlings. We considered the mechanisms involved in the reduction of P and K application rate by PTKPA as follows: 1) PTKPA increased the P content of plant, which accelerated the root establishment. 2) The advanced root establishment not only reduced the duration of water stress, but also increased absorption of the essential nutrients such as N and Mg. 3) Higher content of N and Mg led to higher chlorophyll content and possibly protein content, which activated photosynthesis during the early growth stage. 4) Improved photosynthetic activities increased NAR during the early growth stage. 5) This increase in NAR accelerated leaf expansion, increasing LAI. 6) Larger LAI during the early growth stage led to larger LAI throughout the growing stage, resulting in a higher CGR and ear yield.

Key words: Phosphorus, Plug seedling, Potassium phosphate solution, Pre-transplanting application, Reduction in fertilizer use, Sweet corn.

Phosphate ore, the raw material of phosphatic fertilizers, whose amounts and locations are limited, is said to restrict agricultural production in the near future (Ando, 1983; Yasuda, 1999). On the other hand, the efficiency of phosphatic fertilizer in crop production is generally very low, especially in Andisol or volcanic ash soils because of its very high phosphorus fixation capability as to restrict phosphorus absorption of crop plants (Nishio, 2003). Another reason for the low efficiency in Andisol soil is that the application rate of phosphorus generally exceeds the plant’s demand so as to ensure enough growth during the early growth stage. The excess application of phosphatic fertilizer is not only uneconomical but also results in an accumulation of phosphorus in the soil (Obata and Nakai, 2004), which sometimes causes fertilizer injury in plants (Suzuki et al., 1983; Ohashi et al., 1984; Kawai et al., 1993). Hence, the improvement of the efficiency of phosphorus utilization is required.

Previously, we proposed a new fertilizing system for cabbage, in which potassium phosphate solution was applied to potted seedlings just before transplanting to the field, and termed it “pre-transplanting application of phosphorus to seedling (PTKPA)” (Watanabe et al., 1997, 2005). We also reported that the weight of cabbage head produced by this system is not different from that produced by the conventional fertilizing system, even though the application rate of phosphorus is reduced to 20% of that in the conventional fertilizer system. In today’s vegetable production, machinery transplanting of plug-seedlings is becoming popular as a labor-saving method. It is important to modify the newly proposed pre-transplanting phosphorus application system to the plug-seedlings. However, it is difficult to supply enough phosphorus to relatively salt-sensitive cabbage seedlings grown in cells with limited soil media where salt concentration is expected to become too high.

For these reasons, we tried to improve the method using sweet corn (immature corn) that is more resistant to high phosphorus concentration than
We transplanted plug-seedlings of sweet corn immersed in potassium phosphate solution to the field with reduced amounts of phosphorus application. Then we measured the effects of PTKPA on growth, photosynthetic activity, mineral absorption, and yield. We also studied the possibility of reducing the potassium application rate under this system.

Materials and Methods

Two experiments were conducted, one in 2000 and the other in 2002 at the National Agricultural Research Center for Tohoku Region in Fukushima city located in the northeastern part of Japan (37°42´N, 140°20´E). The soil was a light colored Andisol with pH 6.5 (H2O), 120.9 g P2O5 kg⁻¹ of available phosphorus measured by Bray No.2 method and 18.8 g P 2O5 kg⁻¹ of phosphate absorption capacity. The design of each experiment is shown in Table 1. A randomized block with three replications was used as the experimental design.

### Experiment 1

|            | P (g plant⁻¹) | K (g plant⁻¹) | N (g plant⁻¹) |
|------------|---------------|---------------|---------------|
| **PT-P**   | Basal         | Total         | RR(%)         |
| **C100**   | 0             | 1.257         | 100.0%        |
| **KP50**   | 0.1           | 0.629         | 25.0%         |
| **KP25**   | 0.1           | 0.314         | 33.0%         |

| **PT-K**   | Basal         | Total         | RR(%)         |
|------------|---------------|---------------|---------------|
| **C100**   | 0             | 3.387         | 100.0%        |
| ** KP50**  | 0.158         | 1.694         | 54.7%         |
| **KP25**   | 0.158         | 0.847         | 29.7%         |

| **Basal**  | Topdress      |
|------------|---------------|
| **C100**   | 4.8           |
| **KP50**   | 4.8           |
| **KP25**   | 4.8           |

1) Pretransplanting application of P or K, 2) Percentage of the amount of applied phosphorus or potassium to that in the C100 plot, 3) P2O5ᴺ = 12kg 10a⁻¹, 4) K2Oᴺ = 17kg 10a⁻¹, 5) K2Oᴺ = 15kg 10a⁻¹, 6) N = 20kg 10a⁻¹.

### Experiment 2

|            | P (g plant⁻¹) | K (g plant⁻¹) | N (g plant⁻¹) |
|------------|---------------|---------------|---------------|
| **PT-P**   | Basal         | Total         | RR(%)         |
| **C100**   | 0             | 1.257         | 100.0%        |
| **C25**    | 0             | 0.314         | 25.0%         |
| **C0**     | 0             | 0.000         | 0.0%          |
| **P25**    | 0.1           | 0.414         | 33.0%         |
| **P0**     | 0.1           | 0.100         | 8.0%          |

| **PT-K**   | Basal         | Total         | RR(%)         |
|------------|---------------|---------------|---------------|
| **C100**   | 0             | 2.989         | 100.0%        |
| **C25**    | 0             | 2.989         | 100.0%        |
| **C0**     | 0             | 2.989         | 100.0%        |
| **P25**    | 0.158         | 3.147         | 105.3%        |
| **P0**     | 0.158         | 3.147         | 105.3%        |

| **Basal**  | Topdress      |
|------------|---------------|
| **C100**   | 3.6           |
| **C25**    | 3.6           |
| **C0**     | 3.6           |
| **P25**    | 3.6           |
| **P0**     | 3.6           |

1) Pretransplanting application of P or K, 2) Percentage of the amount of applied phosphorus or potassium to that in the C100 plot, 3) P2O5ᴺ = 12kg 10a⁻¹, 4) K2Oᴺ = 17kg 10a⁻¹, 5) K2Oᴺ = 15kg 10a⁻¹, 6) N = 20kg 10a⁻¹.

1. Experiment 1

Seed of super-sweet corn (Zea mays L., cultivar: Peter Corn) were sown on 22 May 2000 into 128-cell trays filled with composite of peat moss and vermiculite containing 0.2 g N l⁻¹, 1.21 g P l⁻¹ and 0.22 g K l⁻¹.

At the 3rd leaf stage on 9 June the seedlings were immersed into the potassium phosphate solution containing 1.0% P and 1.58% K for 2 hours. The solution was adjusted to pH 6.2 by adding KH₂PO₄ and K₂HPO₄ at the ratio of 3 to 1. Nursery soil in each cell absorbed about 10 ml of the solution, which equals the application of 100 mg P and 158 mg K to each seedling. The seedlings after PTKPA were transplanted to the field where basal dressing of both phosphorus and potassium was reduced to 25% (KP25) and 50% (KP50) of the conventional fertilizer. To the control plot (C100) we applied 52.4 kg P ha⁻¹ and 141.1 kg K ha⁻¹ as superphosphate and potassium sulfate, respectively, and grew plug seedlings by conventional fertilizer system were transplanted. The amounts of P applied to KP25 and KP50 plots were 33 and 58% of the control plot (C100), respectively (Table 1). Nitrogen was applied at a rate of 200 kg ha⁻¹ as ammonium sulfate, and 20 Mg ha⁻¹ of compost made from rice straw was applied to every plot. The fertilizer was dressed uniformly to the top soil. Seedlings were transplanted with 80cm row wise and 30cm of hill distance or 41667 plants ha⁻¹. No material was used to cover the seedlings. Table 1 shows the amounts of P, K and N applied per plant in each plot.

Plants were sampled on 3 July, 24 days after transplanting (DAT) and 19 July (40 DAT), and finally harvested on 16 August (68 DAT). At each sampling, plants were divided into several organs. Leaf area was measured (Hayashi-Denko, AAM-7) and after oven-dried for three days at 90-70ºC, dry weight of each organ was measured. Using these data, crop growth rate (CGR), net assimilation rate (NAR), leaf area index (LAI) and relative leaf area growth rate (RLGR) were calculated.

Photosynthetic parameters were measured on the upper most expanded leaves or the 5th leaf on 22 June and on the 8th leaf on 11 July. Those of the second leaf from flag leaf were also measured. Plant material was measured (Hayashi-Denko, AAM-7) and after oven-dried for three days at 90-70ºC, dry weight of each organ was measured. Using these data, crop growth rate (CGR), net assimilation rate (NAR), leaf area index (LAI) and relative leaf area growth rate (RLGR) were calculated.

Dried samples of each organ were ground.
Phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulfur (S) contents were determined with an ICP (inductively coupled plasma) atomic emission spectrophotometer (Shimadzu, ICPS-8000) after ground samples were digested with nitric acid (Koyama, 1990). Nitrogen (N) content was determined with a CN-corder (Yanagimoto, MT-600).

2. Experiment 2

Sweet corn seeds (*Zea mays* L., cultivar: Peter Corn) were sown on 8 May 2002 into 128-cell trays. After the 4th leaf emerged on 30 May, 1.0% P of potassium phosphate solution was applied (PTPKA) in the same way as the experiment 1. Seedlings by PTKPA were transplanted onto the fields where basal dressing of phosphorus was reduced to 25% or 0% of the conventional fertilizer system (indicating P25 and P0, respectively). In the control plot, P was 100, 25 and 0% of the conventional fertilizer system (C100, C25 and C0, respectively), and the plug seedlings grown by the conventional fertilizer were transplanted. Nursery soil in each cell absorbed about 10 ml of solution, which equals to the application of 100 mg P to each seedling. Consequently, the amounts of P applied to P25 and P0 plots were 33% and 8% of that applied to the control plots, respectively. The rate of potash fertilizer, 124.5 kg ha$^{-1}$, was the same among all the plots in the experiment 2. Nitrogen fertilizer was applied separately at a rate of 15 kg ha$^{-1}$ as basal dressing and 5 kg ha$^{-1}$ as topdressing. Other cultivation conditions were the same as those in the experiment 1 (Table 1).

Results and Discussion

1. Dry matter production, leaf area expansion, growth analysis and yield

Fig. 1 shows the fresh weights of ear at harvest of sweet corn. Ear yield in KP25 and KP50 were equal to or higher than that in C100. We concluded that PTKPA
can maintain or increase sweet corn yield in spite of the reduced amount of P and K application.

Both dry-matter production and leaf expansion during the early growth stage (June 9 - July 3) were increased by PTKPA as shown in Figs. 2 and 3. Increase in dry weight was observed in most plant organs, but was especially remarkable in the shoot, resulting in an increased T/R ratio. Dry weight and leaf area after PTKPA increased rapidly during the mid-growth stage (July 3 - July 19), but the T/R ratio did not change during this period. Total dry weight and leaf area at harvest were heavier and larger, respectively, in the KP50 and KP25 plots than in the C100 plot, but the difference between the PK50 and KP25 were slight.

Fig. 4 shows the results of growth analysis based on these data. PTKPA increased CGR throughout the growing stages. Both higher LAI and higher NAR contributed to higher CGR in PTKPA plots during the early growth stage. Among growth parameters, RLGR during the early growth stage contributed the most to the yield as shown in Fig. 5. From these results, we considered that the higher NAR during the early growth stage leading to the larger LAI contributed the most to the increase in ear yield of sweet corn after PTKPA.

Several reports indicated the importance of P fertilizer as a growth starter in direct sowing of maize (Bullock et al., 1993; El-Hamadi and Woodard, 1995; Mallarino et al., 1999). In these reports, band application of P enhanced P absorption just after germination and advanced the growth in early growth stages, but had no effect on ear yield. In contrast to these results, PTKPA promoted the growth of sweet corn throughout the growing stages. Nutrient condition from transplanting to root establishment...
seemed to have large effects on subsequent growth. In addition, the amount of available phosphorus in soil must be taken into consideration, since the advance of early stage growth did not often result in increase in yield in the field rich in available phosphorus, as Mallarino et al. (1999) pointed out.

On 25 July, silking was observed in 1.9% of the plants in the C100 plot, whereas it was observed in 64.2% and 66.7% of the plants in the KP25 and KP50 plots, respectively. Bullock et al. (1993) reported that phosphorus application as a growth starter in the directly sown corn also advanced silking. These results suggest the advancing effects of high P content on the growth of corn.

Since the corn yield was increased by PTKPA in the experiment 1 even when the amount of applied phosphorus was reduced to 33% of conventional application, we further reduced the amount of phosphorus application in the experiment 2. As shown in Fig. 6, when no P was applied to the field (P0 plot) after PTKPA, the corn yield was nearly the same as that under the conventional system (C100). In this case, also, like the results of the experiment 1, both NAR and LAI increased during the first 4 weeks after transplanting and LAI continued to be higher in the P0 plot than in the C100 plot until the late growth stage (data not shown).

2. Photosynthetic parameters

Fig. 7 shows the net photosynthetic rate (Pn), stomatal conductance (Cs), maximal quantum yield (Fv/Fm) and SPAD value in each experimental plot. At the early growth stage, 13 DAT, all parameters of the 5th leaf were higher in PTKPA plots than in the C100 plot. As shown in Fig. 8, NAR tended to be higher when Pn was higher, although there was no statistical correlation between them. This suggests the advancing effect of PTKPA on photosynthesis in the early growth stage.
stage. After the mid growth stage, however, little difference in photosynthetic parameters was observed between plots.

Since higher Cs values indicate higher stomatal aperture and transpiration rate, PTKPA was supposed to increase water uptake on 13 DAT through promoting root establishment. Lower Cs values in the C100 plot, on the other hand, indicated the lower gas exchange rate between atmosphere and mesophyll. Though intercellular concentration of CO2 (Ci), calculated with a portable photosynthetic meter, was higher in the C100 plot than in the KP50 and the KP25 plot in the present experiment, the actual Ci is often much lower than the calculated value because of unevenness of stomatal aperture over a leaf surface under a water-stressed condition or high abscisic acid condition (Terashima et al., 1988; Downton et al., 1988). In this case, Ci around the closed stomata is considered to drop to the CO2 compensation point, leading to shortage in the acceptor for reducing power supplied from photochemical systems. Consequently, accumulation of excessive reducing power causes photoinhibition. Fv/Fm, a maximal quantum yield in photosystem II (Shcreiber, 1995), usually ranges between 0.8 and 0.83 in the leaf that is not

Fig. 9. Inorganic nutrient content of each organ (-4L : leaves less than the 4th leaf, 5-6L : the 5th and 6th leaves, 7L : leaves higher than the 7th leaf, S : leaf sheaths and stalks, R : roots) of the corn plants grown by the conventional method and after pretransplanting KP application on 24 days after transplanting (July 3).

* and ** : significantly different at 5% and 1% level, ns : not significantly different. Vertical bars indicate standard errors.

Fig. 10. Relationship between amount of phosphorus applied and absorbed by the corn plants grown by the conventional method and after pre-transplanting KP application. Lines in figure indicate phosphorus recovery rate that was calculated with following formula: Phosphorus recovery rate (%) = (Amount of P absorbed by plants in each plot - Amount of P absorbed in C0 plot) / [Amount of applied P] x 100.
photoinhibited, but is reduced by photoinhibition (Björkman & Demmig, 1987; Öquist, 1991). Since Fv/Fm on 13 DAT, as shown in Fig. 7B, were 0.718, 0.761 and 0.763 in the C100, KP50 and KP25 plot, respectively, photoinhibition was supposed to have occurred in all plots. The lower Fv/Fm in the C100 plot was considered to have resulted from delayed root establishment. The water-stress condition caused by delayed root establishment decreased Cs leading to a drop of CO2 concentration in chloroplasts, which finally decreases the CO2 assimilation rate. Tanaka et al. (1982) reported that several enzymes functioning in the Calvin cycle, such as glyceraldehyde-3-phosphate dehydrogenase, can be the target molecules attacked by the reducing power. The activities of enzymes in the Calvin cycle could be inhibited in the C100 plot due to severe photoinhibition. Asada (1999) further pointed out that once these target molecules were inactivated, photoinhibition such as decomposition of chloroplast components will be amplified with vicious sequence; decrease in the acceptor for reducing power, further accumulation of the reducing power, and generation of reactive oxygen species. Lower SPAD values in the C100 plot could also result from the chlorophyll decomposition by photoinhibition in addition to reduced chlorophyll contents.

3. Mineral content

Fig. 9 shows the mineral contents of plant organs sampled during the early growth stage or 24 DAT (Experiment 1). PTKPA tended to increase P content of leaves, especially in leaves below the 4th node. P is known to be easily translocated from lower to upper leaves under insufficient P conditions (Takahashi, 1993). In the C100 plot, P seemed to be translocated from lower leaves to upper leaves during the early growth stage when root could not absorb enough P to sustain plant growth. On the other hand, in our other experiment (Watanabe and Murayama, 2004), P content of leaves in PTKPA plot sampled at 9 DAT were 2.7 times higher than that in the C100 plot. The smaller differences in leaf P content among plots in this experiment seemed to have caused by the dilution effect resulted from larger dry matter production in

![Fig. 11. Relationships between P, N and Mg contents of the 5th and 6th leaves on July 3 and net photosynthetic rate (Pn) on 13 days after transplanting (June 22) in the corn plants grown by the conventional method and after pre-transplanting KP application. ** : significant at 1% level, ns : not significant at 5% level.](image1)

![Fig. 12. Relationships between P, N and Mg contents of the 5th and 6th leaves on July 3 and SPAD value on 13 days after transplanting (June 22) in the corn plants grown by the conventional method and after pre-transplanting KP application. * and ** : significant at 5% and 1% level, ns : not significant at 5% level.](image2)
PTKPA plots. It could be possible to conclude that P content of leaves during the early growth stage was increased by PTKPA. Though no differences in P content among plots were observed after the early growth stage, the P content of plants in the PTKPA plots never fell below that in the C100 plot even at the harvest time (data not shown).

Fig. 10 shows the relationship between total amounts of applied P and those absorbed by plants at harvest (Experiment 2). The recovery rate of P was markedly high in the P0 plot (82.5%) compared with that in the C100 plot (3.7%). Total P uptake by plants in the P0 plot, however, was higher than that supplied by PTKPA. These data strongly indicate that sweet corns after PTKPA could efficiently absorb P from the soil and compost.

There was little difference in the K content among plots as shown in Fig. 9. Even though we have already reported that the K content of leaves after PTKPA was 10% higher than that in the C100 plot (Watanabe and Murayama, 2004), the growth promoting effect of K was considered to be smaller than that of P in this experiment. That because sodium phosphate also enhanced the early-stage growth in cabbage (Watanabe et al., 1997). Mallarino et al. (1999) also reported that the K application or higher K content did not always enhance growth.

On the other hand, Ca, Mg and S content of leaves during the early growth stage in the PTKPA plots were higher, especially in the 5th and 6th leaves, which were the most active leaves at sampling, than in those in the C100 plot. The N content of leaves also tended to be higher in the PTKPA plot although the difference was not significant. Even in the P0 plot (Experiment 2), not only the P content but also the contents of other minerals such as N and Mg were higher than those in the C100 plot (data not shown). We reported that absorption of essential nutrient minerals was often enhanced by PTKPA in wheat and cabbage (Watanabe et al., 2002, 2005). Reinbott et al. (1991) and Skinner and Matthews. (1990) also observed an increase in absorption of Mg and Ca in wheat and grape plants under a high P condition. Thus, the higher P content of plant seems to advance the absorption of these minerals. Increased water secretion from stems in sweet corn after PTKPA suggested the enhancement of root activity by PTKPA (Watanabe and Murayama, 2004). Further studies, however, are needed to determine how the higher P content after PTKPA could be one of the factors that enhanced photosynthetic activity. Since P content of the leaves in the C100 plot was significantly lower than that in PTKPA plots, the photosynthetic activity of the lower leaves in the C100 plot was estimated to be lowered by reduced P content resulting in lower NAR.

Different from the K content of leaves, the increases in N and Mg contents of leaves increased photosynthetic parameters such as Pn and SPAD, and positive correlations were observed between them as shown in Figs. 11 and 12.

4. Conclusion
From these results, we conclude that application of both P and K fertilizer could be reduced by PTKPA to plug seedlings without reducing ear yield of sweet corn. We considered the mechanisms involved in the reduction of P and K application necessary for sweet corn growth by PTKPA as follows; 1) PTKPA increased the P content of plants, and the high P content advanced the root establishment. 2) The advanced root establishment shortened the duration of exposure to water stress and enhanced the absorption of the essential minerals such as N and Mg. 3) The higher content of N and Mg led to higher chlorophyll content, and possibly protein content too, and activated photosynthesis during the early growth stage. 4) Improved photosynthetic activity increased NAR during the early growth stage. 5) The increased NAR accelerated leaf expansion leading to larger LAI. 6) Larger LAI during the early growth stage lead to larger LAI throughout the growth stage, and finally resulted in higher CGR and ear yield. However, further studies are needed to determine how the higher P content advanced root establishment and mineral absorption.

Acknowledgements
We are grateful to Dr. Joji Arihara of National Agricultural Research Center, NARO, for his helpful suggestions and critical reading of the manuscript.

References
Ando, J. 1983. Prospect of the phosphorus resource and future course our country should progress. Jpn. J. Soil Sci. Plant Nutr. 54 : 164-169***.
Asada, K. 1999. Rapid adaptation of leaves to light environment. In Watanabe A. Shinozaki K. and Terashima I. eds., Environmental responses of plants. Shujunsha, Tokyo. 107-119**.
Björkman, O. and Deming, B. 1987. Photon yield of O₂ evolution and chlorophyll fluorescence characteristics at 77K among vascular plants of diverse origins. Planta 170 : 489-504.
Bullock, D.G., Simonson, F.W., Chung, I.M. and Johnson, G.I. 1993. Growth analysis of corn grown with or without starter fertilizer. Crop Sci. 33 : 112-117.
Downton, W.J.S., Lovey, B.R. and Grant, W.J.R. 1988. Non-
uniform stomatal closure induced by water stress causes putative non-stomatal inhibition of photosynthesis. New Phytol. 110 : 503-509.

El-Hamdi, K.H. and Woodard, H. J. 1995. Response of early corn growth to fertilizer phosphorus rates and placement methods. J. Plant Nutr. 18 : 1103-1120.

Kawai, T., Ono, Y. and Naito, Y. 1993. Necrotic disorder in leaves of Japanese radish at high temperature by excessive phosphorus. Bull. Okayama Agr. Exp. Stn. 11 : 47-56**.

Koyama, T. 1990. Plasma atomic emission spectrophotometry. In Committee of experimental method for plant nutrition ed., Experimental method for plant nutrition. Hakuyusha, Tokyo. 142-147***.

Mallarino, A.P., Bordoli, J.M. and Borges, R. 1999. Phosphorus and potassium placement effects on early growth and nutrient uptake of non-till corn and relationships with grain yield. Agron. J. 91 : 37-45.

Nishio, M. 2003. Analysis of the actual state of phosphate Application in arable farming in Japan. Jpn. J. Soil Sci. Plant Nutr. 74 : 435-443*.

Obara, H. and Nakai, M. 2004. Available phosphate of arable lands in Japan. Changes of soil characteristics in Japanese arable lands (II). Jpn. J. Soil Sci. Plant Nutr. 75 : 59-67*.

Ohashi, K., Kumagai, K. and Yoshikawa, M. 1984. Fe deficient chlorosis in the leaves of greenhouse roses induced by excess phosphorus in soil. Environ. Control in Biol. 22 : 47-52*.

Öquist, G., Chow, W.S. and Anderson, J.M. 1991. Photoinhibition of photosynthesis represents a mechanism for the long-term regulation of photosystem II. Planta 186 : 450-460.

Reinbott, T.M. and Bleivins D.G. 1991. Phosphorus interaction with uptake of magnesium, calcium, and potassium in winter wheat seedlings. Agron. J. 83 : 1043-1046.

Schreiber, U., Bilger, W. and Neubauer C. 1995. Chlorophyll fluorescence as a noninvasive indicator for rapid assessment of in vivo photosynthesis. In E.D. Schulze and M.M. Caldwell eds., Ecophysiology of Photosynthesis. Springer, Berlin. 49-70.

Skinner, P.W. and Matthews, M. A. 1990. A novel interaction of magnesium translocation with the supply of phosphorus to roots of grapevine (Vitis vinifera L.). Plant Cell Environ. 13 : 821-826.

Suzuki, N., Yamada, K., Takahashi, K., Toda, M., Nakamura, S. and Mizuguchi, C. 1983. Studies on the nutrient absorption and toxicity of excess phosphorus in greenhouse muskmelon. Bull. Shizuoka Agr. Exp. Stn. 28 : 45-50*.

Takahashi, E. 1993. Essential element - Phosphorus. In Plant Nutrition and Fertilizer. Asakura-shoten, Tokyo. 79-80***.

Tanaka, K., Otsubo, K. and Kondo, N. 1982. Participation of hydrogen peroxide in the inactivation of Calvin-cycle SH enzymes in SO2-fumigated spinach leaves. Plant Cell Physiol. 23 : 1009-1018.

Terashima, I., Wong, S-C., Osmond, C.B. and Farquhar, G. D. 1988. Characterisation of non-uniform photosynthesis induced by abscisic acid in leaves having different mesophyll anatomies. Plant Cell Physiol. 29 : 385-394.

Watanabe, K., Moriya, S., Watanabe, Y. and Fujii, K. 1997. Reduction in phosphatic fertilizer by means of pre-transplanting application. Jpn. J. Soil Sci. Plant Nutr. 68 : 622-628*.

Watanabe, K., Murayama, T. and Niino T. 2002. Studies on the mechanisms of acceleration of early growth by means of pre-transplanting phosphorus application. 1. Pre-transplanting phosphorus application enhanced absorption of N, Ca, Mg and S. Jpn. J. Crop Sci. 71 (Extra 1) : 58-59**.

Watanabe, K. and Murayama, T. 2004. Studies on the mechanisms of acceleration of early growth by means of pre-transplanting phosphorus application. 2. Effects of pre-transplanting phosphorus application on root length and bleeding rate. Jpn. J. Crop Sci. 73 (Extra 2) : 328-329**.

Watanabe, K., Watanabe, Y., Niino, T. and Nitta, T. 2005. Reduction in phosphorus application rate to 20% of the conventional fertilizer system and changes in soil chemical properties with the pre-transplanting phosphorus application to seedlings of cabbage. Jpn. J. Soil Sci. Plant Nutr. 76 : 35-41*.

Yasuda, T. 1999. Finitude of materials of fertilizer, especially phosphatic fertilizer. In Environmental Preservation and New Fertilization Technology. Yokendo, Tokyo. 44-57***.

* In Japanese with English abstract or summary.
** In Japanese.
*** Translated from Japanese by present authors.