FERTILITY MANAGEMENT OF THE SOIL-RHIZOSPHERE SYSTEM FOR EFFICIENT FERTILIZER USE IN VEGETABLE PRODUCTION

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ABSTRACT

Extensive researches on soil-rhizosphere processes have shown that a very small proportion of rhizosphere soil is of critical importance for plant growth and health. The soil-rhizosphere zones occupied less than 5-7% volume of the upper 15 cm surface soil in a vegetable field. Designing sustainable management practices that focus on rhizosphere soil is more efficient and cost-effective for improving crop productivity with fewer agrochemical inputs. The innovative Starter Solution Technology (SST) for applying nutrients directly to the soil-rhizosphere system is proposed in this paper. The SST reduces fertilizer application, increases vegetable yields, decreases fertilizer residues in the soil and is simple to apply. Other practices for managing the fertility of rhizosphere soil, such as supplying nutrients through drip irrigation, applying organic fertilizers and bio-charcoals to increase soil-buffering capacity and localized amendment as strategies for problem soils are also discussed. All of the proposed management practices can be easily adopted by Asian farmers.

Key words: soil-rhizosphere system, starter solution technology, drip irrigation, localized amendment, bio-charcoal application

INTRODUCTION

The rhizosphere concept was first introduced by Hiltner in 1904 to describe the narrow zone of soil surrounding the roots where microbe populations are stimulated by root activities. It thus distinguishes from the "bulk" soil, which is not influenced directly by growing roots. The original concept has now been extended to include the soil surrounding a root in which physical, chemical and biological properties have been changed by root growth and activity (McCully 2005).

By definition, the rhizosphere is the volume of a thin layer of soil immediately surrounding plant roots that is an extremely important and active area for root activity and metabolism. Important physiological processes in this zone are the uptake of mineral nutrients and microbial activity enhanced by root exudates; it is profoundly different from the bulk soil.

Acids produced by microorganisms in the rhizosphere markedly affect nutrient availability. Hence, the rhizosphere is the key soil zone for major root, soil and microbial interactions in the field.

The extent of the rhizosphere's share in the topsoil varies with genotype, nutritional status of the plants, soil conditions and factors that influence root growth. For an annual crop or fruit tree, the rhizosphere soil can constitute between 0.5 to 20% of the topsoil. Welbank *et al.* (1974) reported that the roots of winter wheat occupied about one percent of the volume of the upper 15 cm of soil. Other observations show that the volume of root systems is seldom more than five percent of the surrounding soil. Knowing the differences in the extent of rhizosphere soil is important for determining the best fertilization practices (Römheld & Neumann 2005).

However, major vegetable tap and fibre roots are distributed in the 15cm^3 of soils surrounding the core of the taproot. Therefore, in this paper, the soil rhizosphere system refers to the total volume of the 15cm^3 of soils surrounding the tap roots of a vegetable

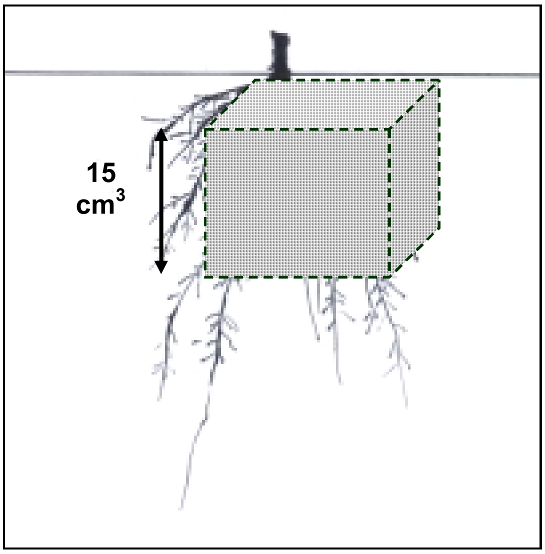

Fig. 1. Proposed soil-rhizosphere zone for nutrient supply and fertility management.

plant (Fig. 1). In general, the volume of a surface soil (top 15cm) is calculated as 1.5 x 10^9 cm^3/ha. While the total volume of 15 cm^3 of soil with a population of 22,200 to 31,200 plants/ha in vegetable fields is estimated at around 0.75-1.1 x $10^8 cm^3$/ha, which occupies 5 to 7% volume of surface soil. Fertility management on this small soil zone is more cost-effective than management on whole bulk soil.

COMPONENTS THAT AFFECT NUTRIENT AVAILABILITY IN THE SOIL-RHIZOSPHERE SYSTEM

Microbial activities and the biological control of pathogens in the soil-rhizosphere system have been extensively studied. However, less attention has been focused on fertility management in the soil-rhizosphere zone due to possible fertilizer burning when fertilizers are applied too close to roots. Due to soil buffering capacity and microorganism function, roots are actually more tolerant to drastic changes of conditions in the rhizosphere than one would expect. Fig. 2 illustrates the components that govern nutrient availability in a soil-rhizosphere system, i.e. plant roots, soil colloid particles, organic matter, soil solution, microorganisms and nutrient ions. This paper focuses on practices that can improve soil-fertility components, such as increased nutrient gradient in soil solution, increased soil organic matter or carbon, increased buffering capacity of soils and adjustments that influence nutrient form and availability such as soil pH.

The Starter Solution Technology (SST) is a recently developed practice for managing soil fertility near the soil-rhizosphere zone. Other existing practices for managing soil-fertility components near the soil-rhizosphere

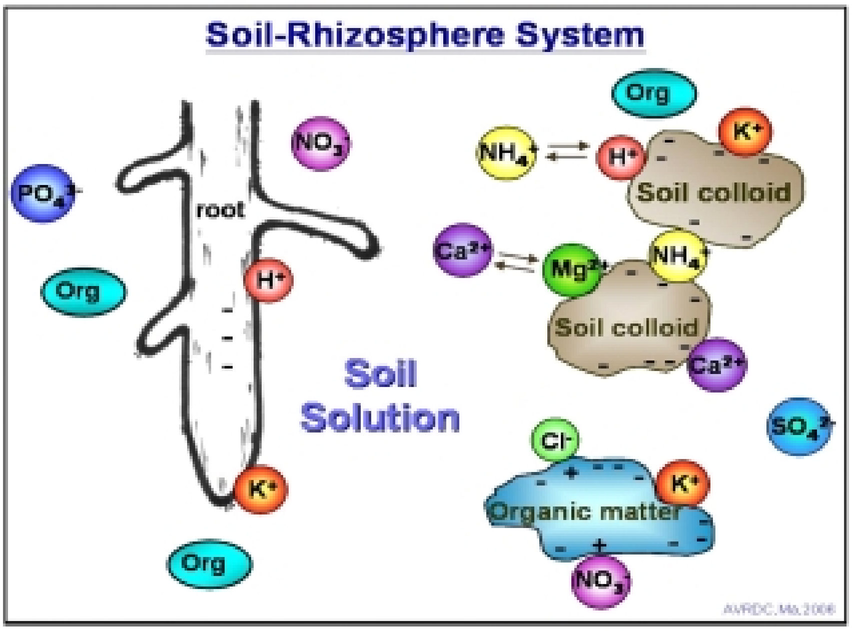

Fig. 2. Components that relate to nutrient availability in the soil-rhizosphere system.

system and that can be used by farmers in developing countries are also summarized.

IMPORTANCE OF SOIL-RHIZOSPHERE PROCESSES AND THEIR RELATION TO PLANT GROWTH

Changes in the Soil-rhizosphere System

Many researchers have documented drastic changes in rhizosphere conditions, such as pH, redox potential, microbial activity and nutrient availability fluxes (Römheld & Neumann 2005). Changes in pH of 2 to 3 units are common within the rhizosphere of distinct root zones and directly affect nutrient availability for root uptake. The magnitude of pH changes in the rhizosphere will depend on plant genotype, nutritional status and soil-buffering capacity (Neumann & Römheld 2002). Farmers can also manipulate rhizosphere pH by applying different forms of N fertilizer, i.e. applying nitrate N to promote pH increase and ammonium N to decrease rhizosphere pH, thus affecting the uptake of different nutrients.

Similarly, the redox potential of soils can also vary over a wide range due to release of root exudates. Changes in redox potential in the rhizosphere may result in Mn toxicity or deficiency in certain crops. Differences in the microbial population found in the rhizosphere can vary 10 to 100-fold compared to the bulk soil because of the release of root exudates and their composition. Another change in the rhizosphere is the accumulation or depletion of mineral nutrients, depending on the solubility of a given nutrient in soil solution and plant uptake. These changes will have significant effects on plant access to water, especially under drought conditions. All of the different rhizosphere processes can have complex interactions. When seeking effective rhizosphere management strategies, farmers need to take into account all rhizosphere changes (Römheld & Neumann 2006).

Importance of soil-rhizosphere processes for plant growth

The rhizosphere acts as a nexus for plant, soil and microbial interaction. Rhizosphere processes are important for plant growth as they improve root growth, enhance nutrient acquisition and protect crops against pests and pathogens (Römheld & Neumann 2006).

Nutrient availability, particularly P and N in the rhizosphere, affects root growth and root hair length. In P-deficient soils, arbuscular mycorrhizae infections often increase as adaptive plant mechanisms. To enhance nutrient acquisition, root growth can be improved by inoculation with certain microorganisms that produce phytohormones. The release of easily degradable root exudates to the rhizosphere can initiate mineralization and turn N into a form more available for plant uptake. Another aspect of delivery of N to plants could be the exchange of fixed ammonium in the clay minerals via rhizosphere acidification (Scherer & Ahrens 1996). Many rhizosphere processes work to replenish rhizosphere soil with water-soluble P. In natural and alkaline soils, rhizosphere acidification induced by NH_4-N supply, can increase acid-soluble Ca phosphate and micronutrient availability. In acid soils, however, rhizosphere acidification will not increase P availability. In contrast, rhizosphere alkalinization, as found in field-grown millet and some legumes, can enhance P availability by improved microbial P mineralization (Neumann & Römheld 2002). Rhizosphere acidification can also efficiently enhance K release either by desorption or by solubilization of K sources with low solubility. All these processes demonstrate the importance of plant root-induced mobilization in the rhizosphere to enhance the nutrient concentration in the rhizosphere-soil solution.

Under certain stressed conditions, plants have higher requirements for distinct mineral nutrients such as K and micronutrients, particularly Mn, Zn and Cu, which are co-factors in various plant defense reactions. It is evident that the availability of Mn in the rhizosphere, as well as of Cu and B plays a decisive role in plant health. Management strategies need to account for enhanced acquisition of these nutrients.

The small area of the rhizosphere soil is an extremely important and active site for nutrient bioavailability, root growth and disease suppression. Best management practices for soil-rhizosphere systems should be based on the knowledge of rhizosphere processes to achieve desired improvements in plant growth and health with less agrochemical (fertilizers and pesticides) inputs. There is great potential to improve fertility management through this new approach that focuses on the soil-rhizosphere system.

PRACTICES FOR DIRECT SUPPLY OF NUTRIENTS TO THE SOIL-RHIZOSPHERE SYSTEM

(1) Application of the Starter Solution Technology (SST) for efficient vegetable production and fertilizer use

Background and rationale

For achieving rapid fertilizer responses, farmers tend to overapply both organic and inorganic fertilizers in intensive farming systems. Excessive applications of fertilizer cause environmental pollution and human health hazards. Improper fertilizer management also results in nutrient imbalance in soils and degrades land in many countries. Asian farmers urgently need judicious fertilization strategies that can improve the efficiency of nutrient uptake by plants and minimize environmental risks.

When a person is sick or injured, the doctor often injects a vitamin supplement because this is the most effective way of supplementing vitamins. Similarly, when a plant's roots are damaged by transplanting, natural trauma or heavy rain, it is crucial to receive an instant, readily available nutrient to facilitate recovery. Based on this concept, researchers at AVRDC developed the Starter Solution Technology (SST) for enhancing early growth and overall yields of the vegetable crops tested (*inter alia*, cucumber, tomato, chili pepper, cabbage, lettuce).

The SST supplies readily available nutrients directly to the soil-rhizosphere system. Small amounts of very concentrated inorganic fertilizer solution are applied to rhizosphere soils immediately after transplanting; they build up high nutrient gradients in the soil solution providing young plants with readily available nutrients before their root systems are well established, thus, enhancing initial growth. Healthy young plants can be more tolerant to environmental stress and increase their early yield, which means more income for farmers.

Unlike field crops, vegetable crops in general have higher nutrient demands in a relatively short growth period. Nutrient uptake directly from the soil particle surface is difficult for plant roots. In general, the roots absorb nutrients from the soil solution. After application to the soil, most nutrients are attached either to soil particles or to part of the organic matter. Only a small proportion of the total nutrients in soils are in solution. Therefore, all the nutrients must be dissolved in soil moisture before plants can absorb them. Sustaining adequate NPK concentrations in the soil solution from sowing to harvesting is crucial for increasing productivity.

In traditional fertilization, farmers apply high doses of fertilizers to sustain high concentrations in the soil solution, resulting in salt accumulation and soil degradation. The SST applies small amounts (less than 1% of maximum soil water holding capacity) of concentrated liquid fertilizer to the soil-rhizosphere system. After adsorbtion on the soil surface and interaction with organic matter, it can still <u>tentatively</u> raise high nutrient gradients in the soil solution around the soil-rhizosphere system. Initial growth of plants and their roots can be greatly enhanced by this single application of the starter solution. When fertilizers are applied in solid form, they need to be dissolved first and then diffused in the root's vicinity. The process may take a few hours or days so it is not able to meet the immediate requirements of the transplants. Direct injection of the starter solution to the rhizosphere soil, similar to injection of booster solutions to plants, provides vital nutrients and has an instant effect on plant growth.

SST development is based on an ecologically friendly concept and principles for plant nutrient requirements. Farmers can easily adjust the concentration and timing of application to fit crop and soil needs. The SST provides a new fertilization option other than conventional fertilization.

Application practices

The principle of SST is to tentatively raise nutrient concentration in the soil solution by one application of **very concentrated** nutrient solution **immediately after transplanting**. According to many experimental results conducted at AVRDC, the optimum concentration of starter solution for many vegetables tested is 240 mg (each) of N-P_2O_5-K_2O in 50 ml for each plant. After conversion to concentration, the starter solution is **4,800 ppm (**mg/l of N-P_2O_5-K_2O**).** Although the concentration of the starter solution is extremely high, after application and interaction with soil clay surfaces, the concentration may decrease to 200-250 ppm N in extractable soil solution. This is the key factor that makes the starter solution so effective. This practice conflicts considerably with the common fertilization application concept; however, it has proven to be effective for many transplanted vegetables. Using a starter solution prepared from a local compound fertilizer (6–12–6% of N-P_2O_5-K_2O) for example, when applied to tomato plants with population of 29,600 plants/ha, the total application rate was only equivalent to 7.2–14.2–7.2 kg/ha of N-P_2O_5-K_2O.

The concentration of the starter solution must be based on soil fertility, soil-buffering capacity, plant species and varieties. The soil at the AVRDC field was silty loam with about 1.5% organic matter and 8-10 meq/100g soil CEC. In general, the lower the soil fertility, the better the effects of the starter solution. For first application of SST, it is necessary to make a preliminary test by transplanting several plants in the field and applying different concentrations of starter solution to each plant, followed by irrigation. If the plants do not wilt or die after one to two days this indicates that the concentration of the starter solution is suitable for the plants.

The booster effect of the SST is best when the soil is dry before application. Due to dryness on the soil surface, the nutrient solution can be adsorbed on the soil surface for some time. On the other hand, the booster effect of the SST is best when it is applied immediately after transplanting and followed by furrow irrigation from the bottom to the top of the beds. The SST can also be applied at later critical stages, such as at head initiation or fruit-setting stages, to replace some inorganic or organic solid fertilizers. When applying the SST, the total amounts of solid fertilizers should be reduced, otherwise, the effects of the SST at later growing stages may not be obvious.

The starter solution can be prepared easily by dissolving soluble fertilizers in water. Any type of locally available soluble fertilizer may be used but the composition of the fertilizers should include N, P and K — the three essential macro-elements. The N form is of critical importance because some crops prefer NH_4^+-N but others prefer NO_3^-N. We suggest that the form best fitted to the crops grown should be chosen. Fertilizers containing urea as N fertilizer should be avoided. Although urea is soluble in water, it needs hydrolysis before plant roots can take it up. The effect of using urea as the starter solution will be less obvious.

The starter solution can be applied manually to the rhizosphere soil of the plant. It can also be applied by injection, either by manual or mechanized sprayers. The fastest speed tested for application is about 2.5 min/ 100 plants.

Boosting early growth of vegetables

Starter solution and fertilizer effects on head cabbage, cherry tomato, fresh tomato, chili and green peppers and cucumber were evaluated in separate trials. Organic fertilizers were banded at 10-15 cm below the surface of raised beds before transplanting. Small amounts of concentrated liquid fertilizer as the starter solution were then applied to rhizosphere soil immediately after transplanting and/or at critical periods. The initial growth of all the tested vegetables was significantly enhanced by one or two starter solution applications compared to those crops grown with organic fertilization practices alone (Table 1). Application of the starter solution near the soil-rhizosphere system immediately after transplanting resulted in improved nutrient concentrations in the soil solution and provided plants with readily available nutrients. The apparent root development enhanced by starter solutions resulted in vigorous and healthy plant growth.

Overall, the boosting effects of starter solution application on initial plant growth were highly evident even within 12 days of application. The aboveground biomasses were

Table 1. The effects of starter solution applied with organic manures on the initial aboveground and root growth of selected vegetables

Fertilizer treatment	Vegetable crop	Survey time (DAT[b])	Top dry weight		Root dry weight	
			g/plant	Index[c]	g/plant	Index
CM*2[a]	Cabbage	12	2.4	100	0.21	100
CM+St_0[d]			3.9	163	0.29	138
CM	Cherry tomato	21	11.1	100	0.67	100
CM+St_0			17.1	154	0.85	127
CM	Fresh tomato	21	3.8	100	0.50	100
CM+St_0			9.9	260	0.90	180
CM	Sweet pepper	16	1.6	100	0.30	100
CM+St_0+St_{12D}[e]			3.2	200	0.38	127
CM	Chili pepper	25	7.2	100	0.73	100
CM+St_0			11.3	157	1.03	141
OF[f]	Green pepper	25	3.9	100	0.58	100
OF+St_0			6.2	159	0.87	150
OF	Cucumber	20	8.6	100	0.59	100
OF+St_0+St_{12D}			11.3	131	0.77	131

[a]Amounts of chicken manure (CM) applied equivalent to x2 inorganic solid fertilizer
[b]DAT = days after transplanting
[c]Percentage of treatment without starter solution application for each trial
[d]Starter solution was applied after transplanting
[e]Starter solution was applied after transplanting and 12 DAT
[f]Local available organic fertilizer

enhanced by 31 to 160% while root growth was increased by 27-80%. Application of nutrients directly to the soil-rhizosphere system may also stimulate microorganism activity. The effects of the starter solution combined with organic fertilizers were generally more obvious than application with inorganic basal fertilizers.

Yield improvements and balanced fertilization

Application of SST with organic fertilizers improved the yields of many vegetables tested. Table 2 shows the yield data of selected treatments for chili pepper in trials conducted for three years.

In 2003, marketable yields from the first three harvests, in treatments applied with solutions and chicken manure compost (CM) were 22% higher than treatment with CM alone. Yields of CM treatment with starter solutions and two solid side-dressings were highest and 25% higher than yields in standard inorganic fertilization (SI) check. The highest cumulative marketable yields from six harvests were achieved in the same treatment, i.e. CM was combined with starter solution and solid inorganic side-dressings at 12 and 36 DAT. The fruit yields were 26% higher than the SI check.

In 2004, yield in treatments applied with starter solutions and solid side-dressing were significantly higher than applied pig manure composts (PM) alone or SI check. Marketable yields from the fourth to the sixth harvests, in treatments applied with solid side-dressing at a later growth stage, were higher than yields from those treatments without solid side-dressing at later stages. This implied that application of solid side-dressing was essential for sustaining the booster effects of the liquid supplements in later production stages of chili pepper. For cumulative marketable yields from six harvests, the highest yield was achieved in the same treatment when PM was supplemented with starter solution at transplanting, two additional liquid solutions 12 and 26 DAT and then side-dressed with solid inorganic fertilizers 37 DAT. The marketable yield was 19% higher than the SI

Table 2. Effects of starter solution and fertilizer treatment on the yield of chili pepper conducted over three years, 2003-2005

Fertilizer treatment	Year/season of the trials	Marketable fruit yield (t/ha) Harvest 1-3	Index	Harvest 4-6	Index	Harvest 1-6	Index
CM[X]	2003-Au	6.0	94	7.8	112	13.8	103
CM + ST_0[Y]	2003-Au	7.4	116	7.6	108	15.0	112
CM + ST_0 + $Side_1$ + $Side_3$	2003-Au	7.9	125	8.9	127	16.8	126
Standard inorganic (SI)[Z]	2003-Au	6.4	100	7.0	100	13.4	100
PM[X]	2004-Sp	13.6	100	10.1	109	25.1	109
PM + ST_0	2004-Sp	15.0	110	9.7	105	24.8	108
PM + ST_0 + ST_1 + ST_2 + $Side_3$	2004-Sp	16.2	118	11.2	120	27.4	119
Standard inorganic (SI)[Z]	2004-Sp	13.7	100	9.3	100	23.0	100
OF[X]	2005-Au	10.0	103	14.4	91	24.3	95
OF + ST_0 + ST_1 + ST_2 + $Side_3$	2005-Au	11.4	117	15.9	101	27.3	107
OF + ST_0 + $Side_1$ + $Side_3$	2005-Au	12.7	131	17.2	108	29.9	117
Standard inorganic (SI)[Z]	2005-Au	9.7	100	15.9	100	25.5	100

[X]Composted chicken manure (CM, 10.4 t/ha); composted pig manure (PM, 17.3 t/ha) and local organic fertilizer (OF, 16.4 t/ha).
[Y]Starter solution (ST) was soluble compound fertilizer # 4 ($N-P_2O_5-K_2O$=14%-28%-14%), diluted and applied at a rate of 240-480-240 mg of $N-P_2O_5-K_2O$ in 50 ml water per plant (equivalent to 7.1-14.2-7.1 kg/ha $N-P_2O_5-K_2O$) for one application after transplanting (ST_0) and at 12 and 26 days after transplanting (ST_1 and ST_2).
[Z]Standard inorganic fertilizer (SI) comprised a basal and x 6 side-dressings at 12, 25, 36, 50, 75 DAT and after the second harvest. Total applications were 300-150-200, 300-195-250 and 300-200-300 kg/ha of $N-P_2O_5-K_2O$ for 2003-Au, 2004-Sp and 2005-Au trial, respectively. The chili pepper variety *Jin's Joy selex* was used for all three trials.

check. Application of starter solution in the SI check did not improve overall yield in this study.

In 2005, the highest yield of the first three harvests was achieved when organic fertilizer (OF) was combined with starter solution at transplanting and side-dressed with two solid inorganic fertilizers at 12 and 38 DAT. The marketable yield was 28% higher than the application of OF alone. Among the organically fertilized plots, those with starter solutions applied at early stages and solid fertilizers side-dressed at critical times of plant growth (12 and 38 DAT) yielded 7 to 17% higher than SI check in cumulative yields of the six harvests.

Results of this study showed the feasibility and economic potential of applying starter solution technology for improving chili pepper production. Applications of starter solution enhance the initial growth of plants; better initial growth of plants can lead to higher fruit yields during early harvests. However, the application of solid side-dressing is crucial in order to sustain the booster effects of the liquid supplements into later production stages.

Results obtained from chili trials were consistent with the previous findings from other vegetables and new possibilities for enhancing starter solution effects can be explored. Maximum yields in cabbage were obtained using organic fertilizers supplemented with starter solution at transplanting and one application after 12 days. The highest yields for cherry tomato were in plots fertilized with CM and either supplemented with one starter solution and two later applications of concentrated liquid inorganic fertilizer or one starter solution supplemented with one solid inorganic side-dressing at 9 WAT. For sweet pepper, the yield was highest in the standard inorganic fertilizer treatment supplemented with one starter solution application after transplanting.

Based on these results, a balanced fertilization strategy was developed. Organic fertilizers are applied as basal, followed by starter solution applied after transplanting and at early growth stages, then side-dressed with solid inorganic fertilizers at later growth stages. Through this approach, starter solution could substitute for 30 to 50% of inorganic fertilizer (basal) and more than 50% of organic fertilizer used during the cropping season. The proper amount and timing of side-dressings used in combination with starter solutions can be developed according to the crop and local conditions.

Enhancement of nutrients released from organic fertilizer

Vegetable crops grown using organic fertilizer alone on an N-equivalent basis to inorganic fertilizer may show reduced plant growth and yields. This is due to the slow mineralization rates of nutrients; in particular, available N from organic composts has been cited as the cause.

An incubation study showed that the application of a starter solution at a rate equivalent to 14-28-14 kg/ha N-P_2O_5-K_2O enhanced nutrient releases from PM- and CM-amended soils. The starter solution increased inorganic N levels from 19 to 50 kg/ha, which helped plants to overcome the shortage of nutrients released by organic fertilizers at the beginning of growing periods (Ma & Kalb 2006). This study provides evidence of the enhancing effect on nutrient releases from manure composts by starter solution application. Although the increment of NPK covers only 3 to 4% of total amounts released, it might be critical to improve plant establishment in the first week after transplanting. These results also indicate that soil N management during the initial 30 days after application of organic fertilizers is important to sustain high yields.

Reduced mineral N residues in the soil after harvest

The effects of SST in combination with organic or inorganic fertilizer on soil residual mineral N were investigated in a tomato trial. The starter solution was an inorganic compound fertilizer No. 5 (10-20-20 of N-P_2O_5-K_2O), diluted and applied at a rate of 240-480-480 mg of N-P_2O_5-K_2O in 50 ml water per plant (equivalent to 7.2-14-14 kg/ha N-P_2O_5-K_2O) after transplanting and at 3, 6, 9, and 12 WAT. The SI fertilizer treatment applied fertilizers at a rate of 330-150-210 kg/ha N-P_2O_5-K_2O. All the treatments received the same rates of total N application.

The soils originally contained 12 ppm of inorganic N before transplanting. The net residual mineral N was inorganic N measured after final harvest minus the original inorganic N content. Net residual mineral N in the soil after harvest was 20.8 ppm for soils applied with CM alone, 19.1 ppm for CM plus one starter solution, 43.5 ppm for CM with one starter solution and two solid side-dressings and 69.8 ppm for the SI plot alone, respectively. At the same rate of N application, the mineral N remaining in the soil from the SI plot was 3.5 times higher than in plots applied with CM alone. Since almost 90% of the residual mineral N is in nitrate form, it is very susceptible to leaching by rain or irrigation and may cause groundwater pollution. Application of starter solution with CM could lower the net leftover mineral N in the soil while sustaining higher yield levels.

In conclusion, the positive effects of starter solution application on initial plant growth were evident. Later in the cropping season, the effects of SST used as a side-dressing on yield varied depending on the vegetable, timing of the side-dressing and other supplemental fertilizers. Balanced fertilization practices based on SST in combination with organic and inorganic nutrient sources can lead to increased fertilizer efficiency, higher profits for farmers and reduced risks of environmental pollution. This technology is very easy to apply and modify for different vegetables; it is a low input, soil-based approach, which may also be applicable to situations wherever excessive fertilizer use prevails or where fertilizers are rather costly for farmers — moreover, leaching can be reduced.

(2) Drip irrigation for managing nutrients and water in the soil-rhizosphere system

Global climatic changes result in uneven distribution of water — either drought or floods — in many regions of the world. Water is increasingly becoming a scarce resource even in the humid tropics. The situation is worse during the dry season in most rain-fed areas. Thus, there is a need to develop technologies that promote efficient use of water and fertilizers in vegetable production. Drip irrigation formerly was a labor-saving practice. It is now a mandatory technology for managing water and nutrients in the soil-rhizosphere system.

High volumes of water application through flooding or furrow irrigation are not efficient. Excessive fertilizer application with furrow irrigation leads to environmental pollution and degradation due to leaching of nutrients into underground water. Direct supply of nutrients through drip irrigation in the soil-rhizosphere system appears to be a low-cost, efficient and affordable technology. Compared to furrow irrigation, drip irrigation uses less water, improves the yield and quality of vegetables, promotes efficient use of fertilizers, reduces the spread of soilborne diseases and decreases the risk of groundwater contamination. A low-cost drip irrigation system developed by the *International Development Enterprises* (IDE, India) uses locally available materials. It is easy to operate, repair and maintain. The customized systems are available in user-friendly kit forms. They are Polytube drip and Easydrip, using micro tubes as emitters, and are meant for small farmland (20-1,000 m^2). They also come in two types: a) micro-sprinkler kit and b) mini-sprinkler kit (Postel *et al.* 2003).

Studies were conducted at AVRDC to adapt micro-irrigation technologies for year-round vegetable production; and to compare water and fertilizer-use efficiencies of vegetables under furrow and drip irrigation systems. Vegetable crops including cucumber, tomato, chili pepper and yard long bean were grown on raised beds and irrigated using either furrow or drip irrigation. Each crop was fertilized with NPK based on AVRDC fertilizer recommendation. However, drip-irrigated crops received half of the total rate applied for furrow-irrigated crops. Results showed that yields under drip irrigation were almost similar or better than furrow irrigation. However, water use in drip irrigation was 45.4, 52.5, 60.7 and 75.3% less than furrow irrigation for cucumber, tomato, chili and yard long bean, respectively. Furthermore, nutrient uptake was more efficient in drip-irrigated vegetables (Table 3, Palada & Wu 2005).

Another field study was conducted during the hot–wet season of 2005 to evaluate the influence of drip irrigation levels and mulching on tomato production and to determine crop water use for efficient application. The experimental treatments consisted of three mulching materials: 1) rice straw, 2) rice straw + silver-coated plastic film and 3) plastic film only. A bare soil (no mulch) control was included in the treatment. All plots were drip-irrigated at two soil moisture regimes: 1) -20 kPa (high) and 2) -50 kPa (low). Tomato variety FMTT 1031 an indeterminate type with known tolerance to tomato leaf curl virus (ToLCV) disease, was used in the study. To reduce rainwater intrusion during heavy rainfall all plots were protected with a plastic rain shelter. Basal fertilizer was applied at the rate of 60 kg N-P-K/ha. This was supplemented with three side-dressing applications of 60 kg N-K/ha at three, six and nine weeks after transplanting. Due to flooding, the trial terminated 68 days after transplanting.

Results indicated that soil temperature in plots with rice straw mulch was generally lower than plots with plastic mulch or a combination of straw and plastic film, 1-2° lower in the morning and 3-6° lower in the afternoon. There was no or little difference in mean soil temperature between the two irrigation regimes.

Table 3. Effect of irrigation method on chili yield, disease incidence, nutrient uptake and water use

Irrigation method	Marketable yield (t/ha)	Southern blight damage (%) (l/plant)	Nitrate-N in petiole (NO_3-N,mgkg^{-1})	Water use	Total N fertilizer appoied (kg/ha)
Drip	37.0	6.3	393	39.3	240
Furrow	32.3	22.2	571	100	420

Table 4. Effect of drip irrigation levels on tomato biomass, LAI, fruit yield at early harvest and total water use

Soil moisture regime (-kPa)	Total biomass at 32 DAT[x] (g/plant)	LAI at 32 DA	Fruit number (No./ha x 1,000)	Marketable yield (t/ha)	Water use (mm)
20	38.1	0.5	62.5	2.8	85.7
50	47.0	0.7	88.9	4.1	17.6

[x] Measured at 32 DAT.

Leaf area index (LAI) and total plant biomass were not significantly different among mulch treatments, but they were higher in plants under the irrigation regime of -50 kPa compared to -20 kPa, suggesting more efficient water use at a reduced irrigation rate (Table 4). Marketable yield was not significantly influenced by mulching materials, but fruit size was significantly larger in plots with rice straw mulch compared with other mulch treatments. Marketable yield was significantly greater in plots under the irrigation regime of -50 kPa compared to -20 kPa. This resulted in higher water-use efficiency in plots under -50 kPa regimes. The study indicated that tomato production during the hot–wet season can be optimized at a lower rate of drip irrigation combined with rice straw mulching and may also reduce nitrate accumulation and buildup in the root zone.

PRACTICES FOR ENHANCING SOIL-BUFFERING CAPACITY IN THE SOIL-RHIZOSPHERE SYSTEM

It is well known that applications of organic fertilizers can supply nutrients to plants and at the same time increase soil organic matter, which will increase the nutrient-holding capacity of a soil. Traditionally, organic fertilizers are broadcast on the surface soil and incorporated uniformly into the soil. However, organic fertilizers decompose very quickly under tropical conditions. The nutrients released from organic fertilizers are also subjected to leaching if the crops do not take them up in time. Application of organic fertilizers or organic amendments in the soil-rhizosphere system may concentrate nutrient ingredients in the soil solution and increase retention time of organic matter in rhizosphere soil, thus enhancing soil fertility in the soil-rhizosphere system.

Lehmann *et al.* (2006) has proposed a new approach to carbon sequestration in terrestrial ecosystems through the application of biomass-derived charcoal (bio-charcoal) onto soil. Bio-charcoal such as burnt rice husk, can act as a soil conditioner enhancing plant growth by supplying and, more importantly, retaining nutrients and improving soil physical and biological properties (Lehmann & Rondon 2006). Bio-charcoal is more resistant to decomposition and can remain in the soil for many years. Higher nutrient retention and nutrient availability were found after charcoal additions to soil; this was related to higher exchange capacity, surface area and direct nutrient addition from charcoal (Glaser *et al.* 2002).

Not all agricultural waste materials are suitable for producing bio-charcoal with the exception of rice husks (FFTC 2001), which have high concentrations of silica entrapping C during combustion. The rice husk ash also contains other mineral nutrients such as Ca, Mg, Fe, Mn and K. Application of bio-charcoal is a new technology to ameliorate components as soil colloid particles and increase soil fertility in the soil-rhizosphere system.

PRACTICES TO MANAGE THE SOIL-RHIZOSPHERE SYSTEM AS STRATEGIES FOR THE AMENDMENT OF PROBLEM SOILS

Localized amendment concept

In considering the rhizosphere, most researchers focus their attention on microorganisms. Many management technologies that focus on the soil-rhizosphere system have been adapted worldwide. However, the concept of managing the small but critical soil-rhizosphere system has not been promoted extensively. When soil degradation expands, the amendment of problem soils based on the soil-rhizosphere system provides new ways to reduce cost and to decelerate deterioration. The amendment of problem soils can be achieved by amending the rhizosphere soils first. Examples are given hereunder:

- Acid soils — liming the acid soils in rhizosphere soils only;
- Alkaline soils — adding sulphur powder to soils near the soil-rhizosphere zone;
- Sandy soils — apply organic fertilizers in rhizosphere soils to retain nutrients and water close to the roots;
- Highly weathered soils — apply lime and phosphorus fertilizers in rhizosphere soils;
- Saline soils — leach away salts near rhizosphere soils by drip irrigation or other tools;
- Sodic soils — apply gypsum near rhizosphere soils to exchange Na with Ca;
- Heavy textured soils — incorporate sand or slowly decomposed residues in rhizosphere soils to improve drainage and aeration.

Other management technology

Apply high bed or high pot technology to avoid flooding near rhizosphere soils; shaping special beds for saline soils to reduce salt accumulation on bed surfaces caused by evaporation are all practices that focus on water management in the soil-rhizosphere system.

CONCLUSION

Fertility-related components and practices to manage or ameliorate these components are summarized in Figure 3. As soil degradation in the world is expanding, the concepts and practices for managing rhizosphere soils deserve more attention and promotion as approaches toward more sustainable agriculture.

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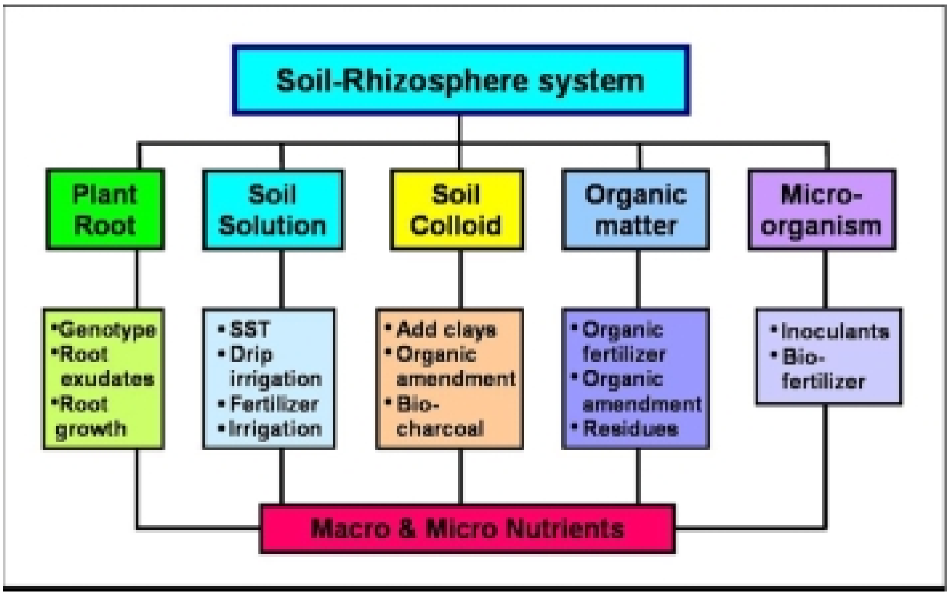

Fig. 3. Practices for managing soil fertility in the soil-rhizosphere system

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