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Merits, Utilization, Perspectives of Controlled-Release Nitrogen Fertilizers

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Summary

This review paper introduces the concept, types, and advantages of controlled-release nitrogen fertilizers especially for some crops' response to these fertilizers, as well as their prospects. From the viewpoint of increasing plant recovery of applied N, improving crop quality (e.g. nutritional quality of vegetables) and avoiding environmental degradation, we can conclude from many experiments mainly conducted in Japan that the controlled-release fertilizers particularly polyolefin-coated fertilizers, showed obvious and great advantages comparing common readily available nitrogen fertilizers. It is important to mention that using controlled-release fertilizers has brought about innovation for whole cultivation systems such as rice. Because of relatively higher prices, currently controlled-release fertilizers only share a very small portion of the fertilizer market and are primarily used in some special crops in developed countries. However, with the increasing attention on the environment and further merits recognition of controlled-release fertilizer by people, as 'environmental friendly fertilizer'—controlled-release fertilizer has a bright prospect both in developed countries and in some developing countries such as China in the near future.

I. Introduction

1.1 Nitrogen nutrition of plants

Nitrogen is one of the most important mineral nutrient elements for existence and maintenance of higher plants' life on this planet. Its main functions are serving as the constituents of many important organic compounds and participating in many essential metabolic processes in plants. Building amino acids, proteins, carriers, enzymes, regulators, nucleic acids, pigments, alkaloids and many other metabolites involve nitrogen for their biosynthesis and interconversions (Marschner, 1997 ; Srivastava & Singh, 1999). However, the juvenile life (during seed germination) of higher plants is self-supporting as far as the nitrogen requirement is concerned. Once the seedlings are established, the roots of plants start acquiring nitrogen and other nutrients from the soil (Srivastava & Singh, 1999).

Nitrate (NO_3^--N) and ammonium (NH_4^+-N) are two major sources of inorganic nitrogen taken up by the roots of higher plants. The nitrate absorbed by roots has to be reduced to ammonia by *nitrate reductase* (NR) and *nitrite reductase* (NiR) in plants, all ammonium directly from the external medium or ammonia from the reduction of nitrate can be assimilated primarily by the action of the key enzymes, including glutamine synthetase and glutamate synthase (Marschner, 1997).

1.2 Importance of nitrogen fertilizers

The population in the future will still grow, therefore, more food must be produced, agriculturally. Considering the continuous increase of the world population and the limitation of the world's reclaimable land's potential resources, both maximizing crop yields and improving quality as well as reducing environmental pollution caused by agriculture practices are urgent subjects (Alexandratos, 1995). Based on the standpoint of environmental protection, the concept and policy of "Low Input Sustainable Agriculture" (LISA) was put forward in the USA in 1990 (Saigusa *et al*, 1997). However, for most developing countries it is impossible to produce a large amount of food by LISA. Within the LISA systems, the cycle of essential nutrients (input and output), including N, keeps a low level in farmland ecosystems. For most soils the available nitrogen supply capacity through mineralization from original organic matter or added organic manure is not always sufficient for sustaining high yields of crops. In most cases nitrogen is the most deficient and a kind of yield restricting factor which determines how high crop yield can attain worldwide, so applying chemical N fertilizers has been an necessary means in modern high-input agriculture.

Today in most populous areas of the world intensive agriculture is being conducted, where nitrogen fertilizers such as urea, ammonium nitrate, and ammonium sulfate etc are very important agricultural production materials, and these readily available N fertilizers have been heavily used. Indeed, excessive input of nitrogen fertilizers have increased crop productivity and subsequently food supply for the world's ever-increasing population was basically guaranteed. On the other hand, the recovery of N fertilizers is always low. This practice has also increased energy input (fertilizer production process, transportation, dressing etc.), and owed to leaching of the excess nitrate to the groundwater and surface water bodies, nitrogenous gases emission through denitrification and ammonia volatilization. Many severe environmental problems were aggravated such as large amounts of nitrate accumulation in vegetable crops, eutrophication in water channels, devastation of ozone layer and global warming (Shoji and Gandeza, 1992 ; Bouwman, 1990).

One approach to increasing the utilization efficiency of N fertilizer by plants and mitigation adverse effect of fertilization is to control the rate of N fertilizer dissolution. This can be done by (i) developing compounds with limited water solubility and (ii) modifying water-soluble materials to delay the release of their contained N to the soil solution. A second approach is to combine N fertilizers with chemicals that control unwanted N transformations in soil, such as nitrification and urea hydrolysis (Hauck, 1985). Thus, various kinds of slow-release nitrogen fertilizers have been invented, produced and utilized, which can provide a solution to the environmental problems mentioned and other agricultural questions, and keeps subsequently affecting environmental upgradation, while maintaining high crop productivity.

II. Concept and types of slow/controlled-release nitrogen fertilizers

2.1 Concept of slow/controlled-release nitrogen fertilizers

Readily available N fertilizers, such as urea or ammonium sulphate etc refer to materials that are dissolved in water immediately after the application. On the other hand, slow release, slow acting, controlled release, metered release, controlled availability and delayed release are some terms used with materials that release their N into the soil at rates and amounts that match the need of the growing plant (Saigusa, 1999). Although there exists nuances among these technical terms, maybe now the most popularly used terms are "slow release" or "controlled-release nitrogen fertilizer", in this paper these two widely used terms which have similar meaning as the whole are preferred.

According to the Association of American Plant Food Control Officials (1995), slow-release fertilizer is defined as the fertilizer containing a certain plant's essential nutrient in a form which delays its availability for plant uptake and use after its application, or which extends its availability to the plant significantly longer than rapidly available nutrient fertilizer (Saigusa, 1999).

2.2 Types of slow/controlled-release nitrogen fertilizers

There are four types of slow/controlled-release N fertilizers: (i) water-soluble materials containing ammonium (NH_4^+) and/or nitrate (NO_3^-) which is covered by a physical barrier, e.g., by a coating; (ii) materials of limited water solubility containing plant-available N forms (e.g., metal ammonium phosphates); (iii) materials of limited water solubility, which, during their chemical and/or microbial decomposition, release plant-available N (e.g., the ureaforms, oxamide); (iv) water-soluble or relatively water-available N that gradually decompose, thereby release plant-available N (e.g., guanylurea salts). The N release rates of all types of slow-release materials can be modified by using chemical additives such as nitrification or urease inhibitors, which affect N transforms in soils (Hauck, 1985).

There is a similar classification method for slow-release fertilizers with the abovementioned (Fig. 1).

However, there has been new advancement in the production of slow-release fertilizers, now there are some coated fertilizers with a nitrification inhibitor, for example, DD-LP (a kind of coated-urea with dicyandiamide).

Nowadays the abovementioned first type of slow-release fertilizers (coated-fertilizers) is relatively produced widely and applied. There are usually three types of coatings applied on the surface of coated-fertilizers: (i) impermeable coatings with tiny holes where solubilized materials diffuse; (ii) impermeable coatings that must be broken by abrasive, chemical, or biological action before N can be released; and (iii) semipermeable coatings through which water diffuses until the internal osmotic pressure ruptures the coating or distends it to increase its permeability. Coatings may play a part only as physical barrier or be a plant nutrient source (e.g., sulfur-coated urea, SCU) (Hauck, 1985). In this paper, all coated-fertilizers will be called controlled-release fertilizers.

Various materials can be used as coatings for solid N fertilizers, including

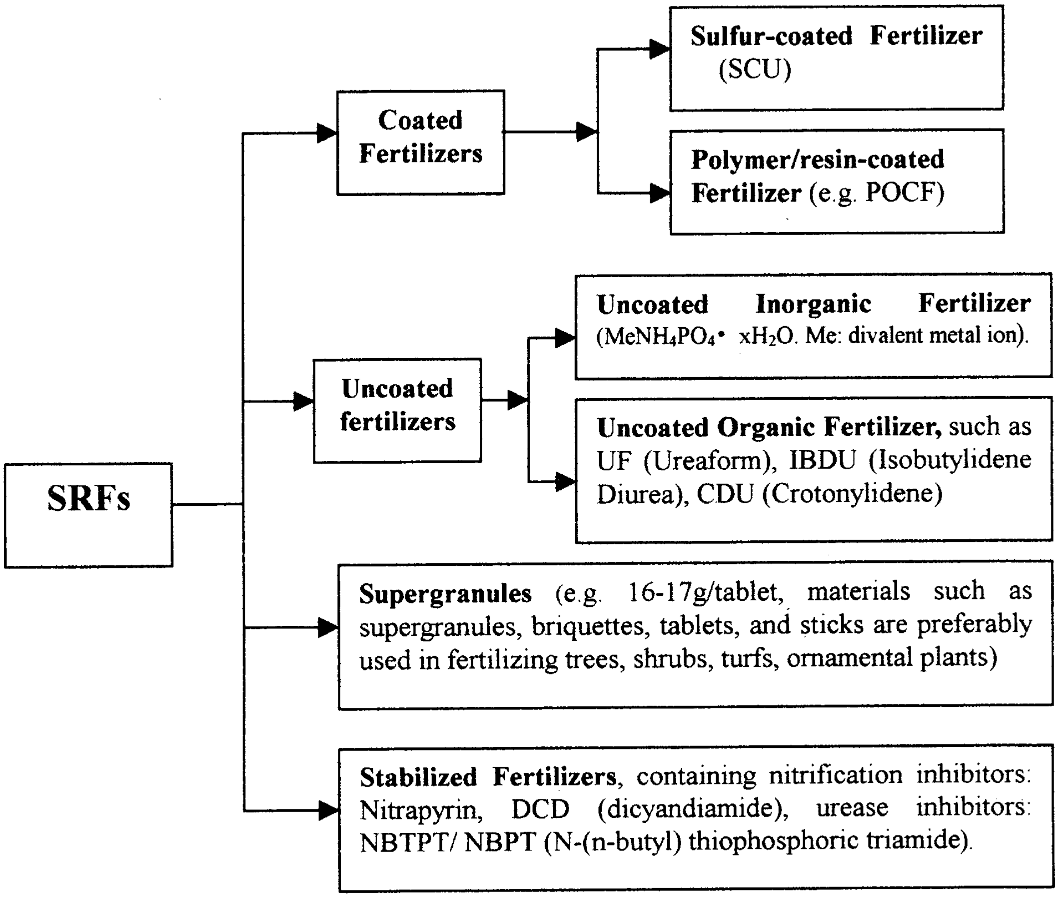

FIG. 1. Classification of Slow-release fertilizers (Saigusa, 1999; Hauck, 1985)

asphalts, tars, gums, latex, oils, paraffin, waxes, acrylic and polymers (PVDC-based copolymers, polyolefin, polyethylene, polystyrene, polyesters, alkyd resins, epoxy resins, polyurethane etc), urea formaldehydes, vinyl acetate, fatty acid salt, rubber, phosphogypsum, peat, sulfur (S), etc., alone or in combination. Among these materials the most commercially important are waxes, S and polymers (Hauck, 1985).

Polyolefin-coated fertilizers (POCF) belong to a polymer-coated fertilizer group, which were developed in Japan and greatly differ from the traditional classes of slow release fertilizers such as sulfur- and wax-coated materials. As far as sulfur- and wax-coated fertilizers, their nutrient release depends on either hydrolytic reactions or microbial attack of the coating. However, the nutrient release of POCF's is not significantly affected by soil properties (pH, salinity, texture, microbial activity, redox potential, ionic strength),but mainly depends on soil temperature and the moisture permeability of the coating when the soil moisture is greater than the initial wilting point (Shoji and Gandeza, 1992). For instance, nitrogen release from POCU (polyolefin-coated urea) can be simulated as a function of either time or cumulative air temperature so that N uptake by a crop can also be simulated, knowing the efficiency of the fertilizer under the prevailing field conditions (Shoji *et al*, 1991).

III. Merits of slow/controlled-release nitrogen fertilizers

Heavy application of readily available fertilizers can cause such problems for plant growth except some environmental problems : ammonium or nitrate accumulation in plant tissue, abnormal internode elongation and increased succulence, resulting in grain loss through delayed maturity, lodging, and susceptibility to disease and pest attack (Saigusa, 1999).

In comparison with rapidly available nitrogen fertilizer, slow-release nitrogen fertilizers have the following potential benefits.

3.1 Common merits of controlled-release nitrogen fertilizers

① Higher nitrogen recovery of controlled-release fertilizers by crops. Due to the nutrient release pattern, the controlled-release nitrogen fertilizer is usually synchronized with the growth rate of crops, lasting nitrogen supply, and recovery of this fertilizer by the crop which is much higher than that of a rapidly soluble one. For instance, in northwestern Japan the comparative recoveries of basal N by ammonium sulphate or urea is only 22%～23% (broadcast, field experiment), whereas POCU-100 (polyolefin-coated urea, broadcast, pot experiment) and POCU-S100 (*Co-situs* application, applied in rice nursery box) by rice plants were 60～62%, 79～83%, respectively (Shoji and Kanno, 1994 ; Shoji and Mae, 1984 ; Ueno *et al*, 1991 ; Kaneta *et al*, 1994).

② Reduction of nitrogen losses and environmental pollution, reduction of salt and/or ammonia toxicity of crops. Increasing the recovery of nitrogen fertilizers by crops means less nitrogen entering into the environment, and the release mode of controlled-release nitrogen fertilizers brings about relatively lower ammonium concentration in growth medium, and therefore is much safer for seeds and seedlings of crops.

③ Simple application method can be easily adopted (e.g. *co-situs* application), application cost is reduced, and innovative farming systems can be developed.

3.2 Characteristics of polyolefin-coated fertilizers

In Japan slow-release fertilizers such as synthetic organic N fertilizers (ureaform, isobutylidene diurea (CDU)) started to be produced in the 1960s. Presently these fertilizers are still utilized for many horticultural crops. Compared with conventional fertilizers, though N availability of these fertilizers is delayed, it is significantly affected by various soil factors including soil acidity, redox potential, soil microbial activities, etc. Therefore, it is difficult to simulate and predict the N release with reasonable accuracy and a rational fertilization program using these slow release fertilizers (Shoji, 1999).

Polyolefin-coated fertilizer(POCF) slowly releases nutrients. In general, the most significant characteristics of these fertilizers are 1) the release of the nutrients is controlled by the prevailing temperature in the environment, and it doubles for every 10°C rise in temperature. The Q_{10} associated with the fertilizer is 2 which matches the Q_{10} for biochemical reactions in plants and microbial activity in many soils, 2) synchronously releasing its nutrient content with the nutrient uptake pattern of most crops (Shoji and Gandeza, 1992). For this reason it is safe for seeds and plant root without causing burns or salt injury. In Japan the *co-situs* application method is popularly used. For instance, mixing seeds with POCF and sowing them using the same mechanical planter, or applying the fertilizer in a narrow band at the desired soil depth and sowing the seeds directly above the fertilizer band as was done for corn. The placement method allows closer proximity of the emerging roots to the fertilizer source, thus resulting in more nutrient uptake and higher fertilizer efficiency.

The nutrient release property of this fertilizer allows wide ranging utilization. In the multicropping system, single basal application can last for 2 to 3 years. Fertilizing water plants is also ok. Many crops (paddy rice, upland crops, horticultural and other permanent crops) and any application method (band, broadcast, etc) is suitable for the fertilizer (Saigusa, 1999).

IV. Studies on application of slow-release fertilizers

Here, rice and some upland crops (vegetables and corn) will be paid much attention to in the discussion.

4.1 Rice

Rice with a very strong adaptability, which can be cultivated in the most diverse environmental conditions, from sea level to 3,000 m in Nepal, from tropic to cold temperate zones, from strongly acidic to neutral soil, from upland to wetland, is one of the most promising crops in the world (Saigusa, 1999).

Now rice is mainly planted in flooded soil where nitrate is easily lost through leaching and denitrification. Therefore, ammonium-N or amide-N-containing fertilizers, such as ammonium sulphate, urea, etc, have been used preferentially in fertilization of wetland rice.

In Japan in recent years there has been much interest in POCU (polyolefin-coated urea) for rice cultivation. Most of the experiments indicated N recovery by rice was much higher than that from conventional urea and ammonium sulfate (Shoji and Kanno, 1994 ; Shoji and Mae, 1984 ; Ueno *et al.*, 1991 ; Kaneta *et al.*, 1994). Rice-transplanting cultivation using POCU with a single basal application of total fertilizers or bulk blending fertilizer of POCU and conventional compound fertilizer, which is thought to be promising fertilization method in rice farming, is being extensively practiced in all parts of Japan. In Southwest Japan where soil is thermic and udic, POCU 140 (means about 80% of total nutrient is released within 140 days in water at 25°C) is recommended by *Japanese Agricultural Association*, while in Northeast Japan where soil is mostly mesic and udic, POCU-100 is recommended (Shoji and Gandeza, 1992). And in cold regions of Northeast Japan the yield and quality of Hitomebore rice can be improved by pot mature seedling cultivation in combination with POCU and dense planting (Saigusa, 1996b).

POCU fertilizers are much more expensive than urea or ammonium sulfate (2 ~3 times), but it is beneficial for the innovation of fertilization and farming systems, whereby the total farming costs can be notably reduced. For example, no-tillage transplanting of rice culture using seedlings with single basal fertilization of POCUs (delayed type of POCU to avoid burning rice seedlings) to nursery boxes can preclude the labour of plowing, puddling, applying fertilizer in the paddy field, and drainage in midsummer. Consequently more than 20% of the total rice-farming cost can be reduced (Sato and Shibuya, 1991).

The most desirable rice-farming system is direct seeding by no-tillage and single basal fertilization using POCU, which can also reduce the growing process of rice seedlings. This system is being conducted in well-drained paddy soil in Japan. Nitrogen recovery from POCU-100 for basal application in this system was much higher than that from conventional ammonium sulfate for basal application (8.5%) (Sato *et al*, 1993). So in a no-tilled rice culture the controlled-release nitrogen fertilizers can play an important role.

4.2 Corn

In Japan, the recovery of applied readily available nitrogen fertilizer by corn (as tall crop) is always low, because the usual occurrence of heavy continuous rain in June and July will disturb topdressing time and enhance leaching losses of N, especially when the root systems of the plants are not yet fully developed. Moreover the N uptake amount by dent corn at the critical level (about 1 m of plant height) was only one-tenth of that at the maturity stage. Also mechanical topdressing is difficult in rainy seasons, and thus it is not very easy to use readily available nitrogen fertilizer by top-dressing to maintain nitrogen nutrition during the late growth stage of corn as a tall crop (Saigusa *et al*, 1993, 1999).

Based on the simulation of corn response to POCU in Andisol under field conditions (Shoji *et al*, 1991), the cumulative N release reached about 80% of the total N content of fertilizer at about 126 days after application or when cumulative air temperature had reached 2,300°C. N uptake from fertilizer followed a typical sigmoid curve. Therefore, the fertilizer can supply the N requirements of corn throughout the whole growing period.

According to dent corn experiments (Saigusa *et al*, 1993), dent corn grown on the plot of a single basal application of POCU showed equal or more amounts of N uptake and yield, higher lodging resistance compared with conventional topdressing. Basal band application of more than 125 kg N/ha of $(NH_4)_2SO_4$ inhibited the growth of dent corn significantly, but not that of POCU at least by 400 kg N/ha. For this reason single basal application of POCU was thought to be a useful method not only for saving labour and maintaining nitrogen nutrition in the late growing stage of dent corn, but also lowering the harmful impact of nitrogen fertilizer on the environment.

Dent corn and sweet corn are two important corn types in Japan. The pot experiment was carried out, which was about influence of *co-situs* application of controlled-release fertilizer on germination rate and root development in the early growth stage of these two types of corns (Nihei *et al*, 1998). Because salt tolerance of dent corn was Larger than that of sweet corn, using *co-situs* placement of polyolefin-coated potassium ammonium nitrate phosphate, germination percentage of sweet corn's was significantly decreased, and development of its adventitious roots was also inhibited. Whereas dent corn showed higher germination rate and its adventitious roots were stimulated very well at a fertilizer placement location. This experiment showed whether *co-situs* fertilization method is suitable for a given crop or not, the physiological characteristics of this crop must be considered.

4.3 Vegetables

In vegetable culture, frequent and heavy application of nitrogen fertilizers is an ordinary practice. Most vegetables as cash crops, high yield is desirable, meanwhile high quality (good external appearance, high nutritional quality) seems to be more important (Saigusa, 1999). Leafy vegetables such as spinach, lettuce, celery etc can accumulate large amounts of nitrate and oxalates, the former can cause methahemoglobinemia and gastric cancer in the human body, and the latter is one of the causes of calculus (Maynard *et al*, 1976 ; Libert and Franchesci, 1987).

Using slow/controlled-release fertilizers in vegetable production has many advantages. The most valuable one is reducing nitrate and oxalic acid content, while at the same time increasing ascorbic acid content through providing long term ammonium nutrition (Ombodi and Saigusa, 2000c). The roots of vegetables can take up ammonium just after being released from the granules of the controlled-release fertilizers. If release rate is higher than uptake rate of the plant, ammonium could accumulate in the fertilization band because concentrated application of ammonium decreases bacterial nitrification activity (Shiviv, 1993). So far many studies on the application of controlled-release fertilizer in vegetables have been carried out in Japan (Ombodi *et al*, 1999, 2000a ; Ombodi and Saigusa, 2000e).

By using coated urea (CU) and coated ammonium phosphate (CAP), the contents of oxalic acid from spinach plants in the CU and CAP plots remarkably decreased compared with those in the common AS plot. NO_3^- was further decreased and sugar was increased in both CU and CAP plots in two cultivars. Total ascorbic acid was increased in the CU plot in three cultivars. Therefore the application of controlled-releasing nitrogen fertilizers induced a desirable effect on the quality of spinach (Takebe *et al*, 1996). Ombodi *et al*. through pot experiments also achieved that in comparison with conventionally used ammonium-sulfate (AS, 21-0-0), four POCFs, which were polyolefin-coated urea (POCU, 40.0-0-0), polyolefin-coated urea containing dicyandiamide (POCU-DD, 41.1-0-0), polyolefin-coated diammonium-phosphate (POC-DAP, 16-40-0), and polyolefin-coated ammonium-sulphate (POC-AS, 18-0-0), respectively, can improve the nutritional quality of spinach plants. And it was concluded that the improvement of nutritional quality (lower contents of oxalate and nitrate and higher content of ascorbate) of spinach by band applications of urea or ammonium containing POCFs was due to realized ammonium nutrition and/or less amount of available fertilizer N. Also the nutritional quality was the best when ammonium nutrition was realized, especially in the POCU-DD treatment (Ombodi *et al*, 1999, 2000a).

The experiments using band application of POC-DAP (polyolefin-coated diammonium phosphate) showed that the nutritional quality of rhubarb, Swiss chard and garden sorrel could be improved (Ombodi A. *et al*, 2000c, 2000d). Using polyolefin-coated fertilizers, nitrate content in lettuce could be reduced without any significant yield decrease, and for this purpose band application of POC-DAP proved to be the most effective method (Ombodi and Saigusa, 2000e).

In the case of the fertilization method, in Japan some of the pepper growers have already been using the band application method for polyolefin-coated urea. However, according to field experimental results (Ombodi *et al*., 2000b), POCF broadcast treatment produced the best yield while POCF band treatment and RAF treatment had similar results. By using POCF, labor and energy costs and environmental loading can be reduced without any yield decrease. Broadcast application of POCF is a more effective method than band application for green peppers grown on Andisol, because of the better early growth, in the case of broadcast application and the extremely low soil solution in the fertilizer band, consequently (Ombodi *et al*., 2000b).

Hochmuch (1992) concluded in his review that controlled-release N sources have the highest utility for long-term crops such as peppers, tomatoes, and strawberry, because using controlled-release fertilizers, the continuous supply of nutrients can be maintained and potential salt injury can be avoided throughout the growing period, and thus balanced plant growth can be achieved (Hochmuth, 1992).

In addition, liberal application of nitrogen fertilizers in vegetable production has resulted in high nitrate concentration in the groundwater in the fields of vegetable cropping in Western Europe and Japan (Prasad and Power, 1995; Kumazawa, 1999). For example, in Nagano prefecture of Japan, when 508 kg of N per hectare was applied to leafy vegetables, an average of 279 kg N was leached out into the waters (Takeuchi, 1997). Field experiments by isotope recovery method showed using polyolefin-coated urea could greatly improve nitrogen use efficiency of tendergreen mustard, and thus decreased the potentiality of nitrate leaching during rainy seasons (Ombodi and Saigusa, 2000e).

4.4 Other crops

In the USA, controlled-release N fertilizers are mostly used on ornamentals, lawns, and professional turfgrasses, but there is a growing tendency toward using them for high-cash agricultural crops under special situations, which include crops growing under mulch, in highly permeable soils in high rainfall areas, and under conditions where nitrification/denitrification is almost certain to occur, e.g., in direct-seeded, flooded rice cultures (Hauck, 1985).

In fact, in Japan controlled-release fertilizers are extensively applied to many crops and are called "Environment friendly fertilizers", even rice farmers are familiar with the merits of this fertilizer (Saigusa, 1999).

As for soybeans, study on alleviations of the depressive effect of nitrogen application on nodulation and N_2 fixation has been carried out using controlled-release fertilizers (Takahashi *et al*, 1991a). The experimental result indicated that acceleration rather than depression of N_2 fixation by the deep placement of POCU-100 lasted throughout the growth stages until maturity. So, deep placement of slow/controlled-release nitrogen fertilizer for soybean cultivation perhaps is a feasible method to obtain a high seed yield compatible with N_2 fixation.

On container plants, in Ohio state and northeastern US most container nurseries mainly used slow-release fertilizers, whereas readily available fertilizers are used only as supplements. Nowadays in the USA slow-release fertilizers are widely used in container nurseries of ornamental landscape such as azalea, juniper, cotoneaster, spindle tree, Alberta spruce, sweet fern, holly *Thuja* etc (Smith and Treaster, 1992).

4.5 Innovation of fertilization method by using coated fertilizers

In general, controlled-release fertilizer which has enabled *co-situs* placement and a single basal application will greatly help to control the adverse effects of fertilization (Shoji, 1999). The central concept of *co-situs* application is to apply a large amount of controlled-release fertilizer in the intensive rooting zone with release patterns that synchronize the plant demand over the whole growing season (Shoji, 1999). The *co-situs* application can significantly increase N use efficiency, for example, using *co-situs* placement wetland rice absorbed approximately 80% of basal MEISTER (a kind of controlled-release fertilizer) N (Ando, 1995; Kaneta *et al*, 1994).

Rice production holds a very important position in Japanese agriculture. Farmers usually apply readily available N fertilizers such as urea or ammonium sulfate at transplantation to stimulate rapid establishment of the rice during the early growth stage. However, such fertilizer practice encourages N losses especially by leaching and denitrification. Multiple split application of N fertilizer can reduce N losses, but operating costs will be increased, too. Alternatively, a single basal application for total N fertilizer through using controlled-release fertilizer can supply enough N to the rice plant during the whole growth period to achieve satisfactory grain yield, and shows much higher recovery in comparison with rapidly available fertilizer (Date and Schio, 1997).

This so-called "A Single Basal Dressing for Total Nitrogen Fertilizer" for paddy rice, a single basal dressing of the controlled-release fertilizers at sowing stage can meet all N demands for the rice's life. As a result several top-dressings can be exempted during the growth period, and labour and energy for top-dressing can be saved (Date and Schio, 1997). This practice also demands using a small amount of readily available N fertilizers and phosphorus, potassium fertilizers at the early growth stage. According to climatic conditions, variety of crops, soil types, as well as nutrient release model and characteristics (e.g. days of nutrient release) of coated fertilizers or chemical synthesizing slow-release fertilizers, fertilizer types can be properly chosen and used. Because of high recovery of N fertilizers, the potential of environmental degradation dramatically decreased. A lot of rice field experiments were conducted in different prefectures of Japan, in which total nitrogen fertilizers were basal dressed to the paddy fields through applying controlled-release fertilizers with conventional fertilizers meanwhile (the applied controlled-release urea usually occupied 50%-80% of total nitrogen amount) (Date and Schio, 1997). Among these experiments, some showed a relatively high yield increase rate (5%-35%) in comparison with only applying conventional fertilizers under conventional fertilization method, whereas the majority of these experiments demonstrated almost the same yield level. However, comprehensively assessment of (considering reduction of fertilization amount and labour, fine environmental effect), applying controlled-release fertilizers showed very big advantages.

The field experiment, whose objectives were to establish no-tillage transplanting of rice by using controlled-release fertilizers in different representative paddy soils of northeastern Japan, was carried out (Saigusa *et al*, 1996a). The results indicated that the new cultivation method for a rice "no-tillage transplanting system with controlled availability fertilizer" was feasible to reduce both labour costs, fossil fuel, soil erosion by elimination of plowing and puddling while

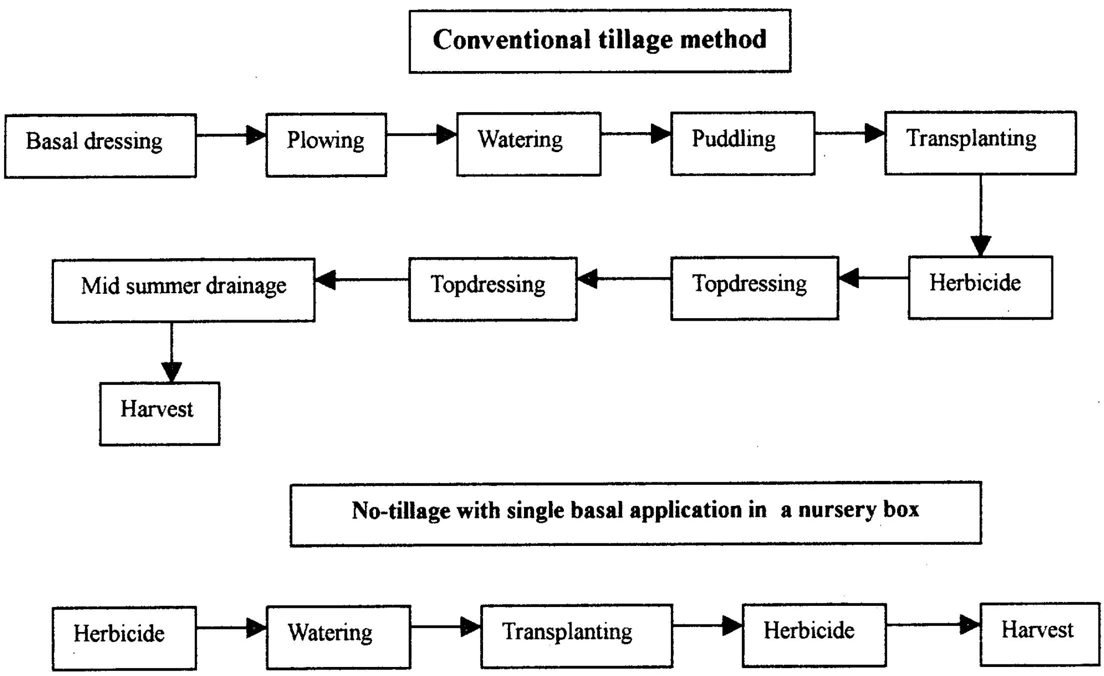

FIG. 2. Comparison of operations required in conventional cultivation and NT cultivation with single basal application of fertilizer in a nursery box (Saigusa *et al*, 1996a)

maintaining high yield (Fig. 2). Therefore, using controlled-release fertilizers and NT (No-tillage) transplanting systems allows the development of a new rice culture indicating MEMPA (maximum efficiency minimum pollution agriculture) (Saigusa *et al*, 1996a). After 5-year studies, Ito *et al* concluded that the no-tillage system with a single basal application of polyolefin-coated urea was highly feasible for silage-corn production in Andisol under humid climate in Japan (Ito *et al*, 1997).

In addition, some experiments concerning tomato, eggplant, cucumber and garlic etc cultivated in the open and allium in the greenhouse were carried out. "Method of A Single Basal-dressing of Total Nitrogen Fertilizer" for upland and horticultural crops can be practiced in the near future (Date and Schio, 1997).

V. Conclusions and future prospects

5.1 General evaluation

It is well known that rapidly available nitrogen fertilizers are one of the main causes of serious agro-environmental problems, such as groundwater and stream water pollution, excess accumulation of nitrate or nitrite in plant, ozone layer destruction, "ozone holes" and soil degradation by salt accumulation or acidification (Shoji and Gandeza, 1992; Shaviv and Mikkelsen, 1993).

Generally, the nitrogen release patterns of controlled-release fertilizers are synchronized with the growth rate of the crops and the recoveries of these types of fertilizers by the crops are remarkably higher than those of a rapidly available one. Owing to high N recovery by crops, environmental pollution caused by nitrogen fertilizer is noticeably reduced and controlled-release fertilizers are evaluated to be an environmental-friendly fertilizer (Saigusa, 1999). Further investigation on the new functions of these fertilizers that supply an aimed form of nitrogen in soil conditions will be needed, using conditions, types and scope of crops which controlled-release fertilizers are suitable for need investigating carefully.

Up to now, we have not found out from papers, in regard to other shortcomings of controlled-release fertilizers except high prices. Under the conditions of *co-situs* placement, even if the recovery of these fertilizer can be greatly increased, however, it is not good enough for some crops such as corn which has high plant height. These crops need a flourishing root system which can be distributed in a wide range of the soil layer so to resist lodging. The *co-situs* placement method perhaps can restrict the roots in a relatively smaller scope, in this case lodging easily occurs.

5.2 Utilization situation of controlled-release fertilizers

Although controlled-release fertilizers with evident and huge advantages, the amount being used now merely occupies a small part of the world's total mineral fertilizer consumption (0.15% in 1995/96). The major reason for this is the high price of these fertilizers. For instance, the price of polyolefin-coated fertilizers' is usually 4 to 8 times of the corresponding readily available fertilizers (Trenkel, 1997). In Japan, polyolefin-coated fertilizers are 2~3 fold more expensive than their corresponding readily available fertilizers (Saigusa, 1999), where the use of polymer-coated fertilizers exceeds 50% of the world's total. In general, the amount of controlled-release fertilizers used had shown a fast increase rate during 1983 to 1996 in the USA, Western Europe and Japan, which had increased at 76.2%, 14.5%, 170.5%, respectively, and the world market is growing at an annual rate of 4.5% to 5% (Trenkel, 1997).

So far controlled-release N fertilizers are mainly used in developed countries. Even in the USA, controlled-release N fertilizers are mostly used on ornamentals, lawns, and professional turfgrasses, but there is a growing trend toward using them for high-cash agricultural crops under special situations.

5.3 Prospects

In Japan, where the labor cost of farming is rapidly rising, POCFs are being extensively applied to a variety of crops. These crops include wetland rice (*Oryza sativa* L.), corn (*Zea mays* L.), soybean (*Glycine max* L. MERILL), wheat (*Triticum aestivum* L.), horticultural plants, and as well as in the process of a rice nursery. Japanese farmers have been achieving a better understanding of the characteristics of this kind of fertilizer and the merits of its application (Shoji and Gandeza, 1992). Besides controlled-release fertilizer's benefits to the environment, in agriculture the cost of labors is very expensive, and agricultural machinery is widely used, therefore, saving the cost of labor and energy is always given preferential considerations, undoubtedly elimination of topdressings means decreasing cost of labor and energy. In general, controlled-release fertilizers have a very bright future in developed countries like Japan.

China is a typical developing country with a large population. So far about 60 percent of the total population live in the countryside, agriculture has always been given much attention, and utilizing fertilizers is one of the main means of increasing crop yields. In recent years many kinds of agricultural products have been overproduced, and relatively speaking the prices of grain, edible oil, vegetables and fruits even including eggs, milk, and pork have drastically decreased. Some places of bumper harvest has not brought about good economic benefits to farmers. For this reason farmers' enthusiasm and input for agricultural production has somewhat gone down, too. Nowadays, the price factor is still of primary obstacle for farmers to use controlled-release fertilizers. If expensive controlled-release fertilizers offer little or no obvious economic advantages over conventional fertilizers for crop production, farmers will first choose cheap conventional fertilizer. However, in the near future, with rapid economic development in some developed areas especially in Southeast China, many people have moved into cities to go in for non-agricultural industry. Farmlands are gradually being shifted to some families, scale of cultivation land is being enlarged, economic benefit has been increased, fertilizer prices are becoming the non-decisive factor for farmers to use fertilizers, at the same time, with market expansion of controlled-release fertilizers', the price of these fertilizers perhaps will decrease to some extent, so in the long run these environmental friendly fertilizers —controlled-release fertilizers will be welcomed by users.

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