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CONTROLLED RELEASE FERTILIZERS

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I. RATIONALE

A. Food Production and Fertilizers: Global Aspects

In 1950, fertilizers comprised only a small percent of the nutrients needed for grain production, most of the supply being provided by the “natural fertility” of the soil and added manure (IFA, 1999). By 2020, more than 70% of the grain yield will have to depend on fertilizers! The demand for plant nutrients is expected to increase continuously with population growth particularly in developing countries. World population is expected to increase by about 2.3 billion by 2020 and double by the year 2050. If meat and food consumption in developed countries is matched by the rest of the world by the mid-21st century, then grain and nutrient demand is expected to triple (Keeney, 1997;). Keeping in mind that the amount of land used for food production changed very slightly over the past few decades (FAO, 1999), and may even have decreased in parts of the world due to urbanization (Keeney, 1997), the nutrient load per unit area is steadily increasing. All this implies that food production will have to be much more intensive and efficient than ever before.

Nitrogen, the most widely applied plant nutrient, has often been until recently singled out for its adverse effects on the environment, as well as on human and animal health (Keeney, 1997). In the last years researchers and environmentalists started to realize the severeness of the environmental problems associated with phosphorus application to soils. Smil (1999) stated that human activities have roughly doubled the amount of reactive N entering the element’s biospheric cycle. Crop production is by far the single largest cause of this anthropogenic alteration. Anthropogenic inputs of N in fertilizers, irrigation water, seeds, etc. supply about 85% of the 170 Tg N yr⁻¹ annually reaching the world’s cropland (Smil, 1999). The global agricultural output of N is about 23 Tg N y⁻¹ (Bockman and Olf, 1998). This implies that the overall efficiency of N utilization for food production is low. Nutrient recovery from N fertilizers may vary with crop species, management practices, soil properties and environmental conditions, and nutrient source (Shaviv, 2000). Trends in crop production and N fertilizer use in the US and the UK were reviewed by Bock and Hergert (1991) who showed that N removed from fields in harvested corn grain tripled over the past 40 years whereas the rate of N fertilizer application to corn increased more than 15 times during that period. Similar trends for global arable and permanent croplands (Kaarstad, 1997 ; Bockman and Olf, 1998).

Thus, despite the remarkable developments in crop production over the past four decades, nutrient use efficiency (NUE) or recovery, especially that of N, remained low. This poses serious concerns regarding environmental, health, energy and resource conservation aspects, especially in the light of the much greater N fertilizer use than removal, and considering the significant increase of nutrient application per unit area.

B. CRFs for Improved Management of Nutrient Application

One possible way to improve nutrient and particularly nitrogen use efficiency while reducing the environmental hazards is by using controlled release or slow release fertilizers (Hauck, 1985; Shaviv and Mikkelsen, 1993; Peoples et al., 1995; Bockman and Olf, 1998; Shaviv, 2000, 2001). Compared to the large amount of fertilizers used throughout the world, the total use of slow and controlled release fertilizers (SRFs and CRFs) is still very small despite the fact that use of CRFs has almost doubled over the past decade (Trenkel, 1997; Shaviv 2001). The greatest consumption and production of CRFs/SRFs is in the US, Canada, Japan and Europe. A significant proportion of these fertilizers is consumed in non-agricultural markets (e.g., for lawn care, golf courses, landscaping). with encouraging signs of increased use for intensively grown crops (vegetables, fruit trees) and rice.

This review examines the possible contribution of controlled release (SR/CR) fertilizers to the improvement of nutrient supply management while minimizing environmental hazards. To enable a better understanding of CRFs, they are classified according to mechanisms of action. Special attention is paid to their modes, length and patterns of release, quantitative description (models), and significance for improved utilization of CRF. Special reference is made to assessing release characteristics and its effects on agronomic and environmental benefits and to efforts in improving the characterization and standardization of CRF.

II. POTENTIAL ADVANTAGES OF CONTROLLING NUTRIENT SUPPLY

The effectiveness of nutrient supply control in increasing nutrient use efficiency (NUE) and reducing environmental problems depends mainly on two factors: matching nutrient supply with plant demand and maintaining nutrient availability.

Complex interactions (or competition) between plant roots, soil micro-organisms, chemical reactions and pathways for loss affect nutrient availability in the soil-plant system. Most of the transformations that nutrients undergo in soil are concentration dependent. This implies that any supply of nutrients exceeding the plant's uptake ability is likely to evoke processes that will decrease its concentration in the soil. Such processes include transformations induced by microbes (e.g., nitrification, denitrification, immobilization), chemical reactions (e.g., exchange, fixation, precipitation, hydrolysis), and physical processes (e.g., leaching, runoff, volatilization). The extent to which nutrients may be removed from soil solution by processes competing with plant uptake can thus affect NUE and the environment. Improved management practices should both temporally and spatially reduce the surplus supply of nutrients.

Total nutrient requirement, specific periods of peak demand, and preferred chemical forms are specific to each crop and variety. The time pattern of macro-nutrient uptake by seasonal crops is generally sigmoidal (Shoji and Kanno, 1994). This is also the general case regarding perennials or trees when a shift from dormant to biologically active phases occurs. Therefore, synchronizing nutrient supply with plant demand using a sigmoidal pattern of supply will provide optimal nutrition for plant growth and reduce losses by the processes competing with nutrient uptake (Oertly, 1980; Hauck, 1985; Shaviv and Mikkelsen, 1993; Shaviv, 1966).

The economic, physiological and environmental advantages associated with controlling nutrient supply are further discussed in light of these two important factors.

A. Economic Aspects

From a practical point of view, nutrient losses via the above-mentioned processes may be considered “irreversible” at least in the short range. Some of these processes are the main cause for the very poor recovery of N ranging from between 70% in better managed practices to 30 – 40% in poorly managed ones such as paddy rice.. Numerous publications deal with the possibility of reducing such losses by using CRF/SRFs or bio-amended ammonium fertilizers (e.g., nitrification inhibitors) (e.g., Oertly, 1980; Allen, 1984; Hauck, 1985; Shaviv and Mikkelsen, 1993; Trenkel 1997, Shaviv, 2000).

Controlled release fertilizers can meet the crop nutrient demand for the entire season through a single application, involving savings in spreading costs. CRFs displaying a lag in release could be used to apply nutrients prior to the “annual spring rush,” or when trafficability in the field is less restricted, such as fall application for winter- or spring-planted crops. Moreover, CRFs can reduce the demand for short-season manual labor for top dressing, such as for rice paddies (Shoji and Gandeza, 1992), that is required during critical periods.

B. Physiological Aspects

In addition to the possible direct savings associated with the use of SRF/CRFs, there are several agronomic advantages related to the improvement of plant growth conditions, as presented below.

- Excessive nutrient supply, commonly resulting from an application of conventional soluble fertilizers, may result in a high concentration of soluble salts in the root zone (Shaviv and Mikkelsen, 1993; Trenkel, 1997). This may induce osmotic stress and cause specific injuries to plants at different growth stages, or undesired development such as lodging. Compared to soluble fertilizers, the use of CRFs involves improved germination and crop quality together with reduced leaf burns, stalk breakage and disease infestation (Allen, 1984; Hauck, 1985; Trenkel, 1997).
- Reduced plant availability of nutrients, such as P or microelements, occurs in many soils as a result of “fixation” processes that reduce the concentration of these nutrients in soil solution. In general, the reactions are concentration dependent. This implies that one single application of highly soluble nutrients is likely to result in a rapid reduction of the available forms (Shaviv, 2000). Controlled release of nutrients into a “fixing” medium may increase their availability (Oertly, 1980). Shaviv (2000) reported a much higher P accumulation in plants fertilized with CRFs containing N-P-K, as compared with applications of conventional granular P.
- A great deal of attention has been paid to the supply of the preferred forms of plant nutrients, particularly regarding the supply of ammonium or nitrate nutrition. Significant increases in grain yields and protein content induced by mixed ammonium-nitrate nutrition compared to nitrate or ammonium alone have been reported (Shaviv, 2000). These results were obtained only in experiments where reasonable control over the ammonium/nitrate ratio in soil could be achieved. Controlled release fertilizers that contained higher proportions of NH_4 produced greater yields of millet and induced an increased accumulation of proteinaceous material (reduced-N) in plants.
- Abundant evidence is available on the synergistic effects between different types or species of nutrients, particularly when they are simultaneously supplied or co-placed near absorption sites on the root surface. For example, it has been shown that ammonium or potassium can significantly increase the availability of Fe in calcareous soils due to the physiological acidification of the rhizosphere (e.g., Marshner, 1986).

Ammonium was found to increase P bio-availability when its nitrification rate was reduced, presumably via the rhizosphere acidification mechanism. Another synergistic effect illustrates the importance of adequate K when plants are supplied with mixed ammonium-nitrate nutrition. Realization of the advantages suggested by the above-mentioned physiological effects can be achieved through proper control over the pattern and chemical form of nutrient release from CRFs. In this respect, the best results are expected with compound CRFs containing N-P-K (with proper ammonium to nitrate ratios) and microelements. Yet, one should bear in mind that at this stage, the variety of granular compound fertilizers qualifying for the prevailing methods of manufacturing CRFs is limited.

C. Environmental Aspects

As shown above, nutrient losses to the environment depend on their concentration in soil solution. Therefore, any nutrient application method that improves NUE, and consequently reduces the surplus of nutrients over plant needs, also has the potential to reduce losses to the environment (Oertli, 1980; Hauck 1985; Bockman and Olf, 1998). Shoji and Kanno (1994) and Shaviv (1996) illustrated this rather simple principle in experiments in which nitrogen release from CRFs was well-synchronized with plant demand.

III. TERMINOLOGY: CONTROLLED AND SLOW RELEASE FERTILIZERS

A. Slow Versus Controlled Release

The term CRF recently became acceptable when applied to fertilizers in which the factors dominating the rate, pattern and duration of release are well-known and controllable during CRF preparation (Shaviv, 2000). Slow release fertilizers (SRFs) involve the release of the nutrient in a slower manner than common fertilizers. However, the rate, pattern and duration of release are not well-controlled. They may be strongly affected by handling conditions such as storage, transportation and distribution in the field, or by soil conditions such as moisture content, pH, wetting and drying, thawing and freezing, and biological activity (Shaviv, 2000). According to Trenkel (1997), it became common to denote the microbially decomposable nitrogen products, such as urea-formaldehyde, as SRFs. In a broad sense, nitrogen fertilizers in which ammonium or urea are “stabilized” (Trenkel, 1997) or “bio-amended” by inhibitors (Hauck, 1985) may be classified as “slow acting nitrogen.” These fertilizers are expected to be effective in soils having a medium to high cation exchange capacity and a good storage capacity of ammonium and other nutrients.

B. Systematic Classification

Controlled and slow release fertilizers can be generally classified into the following three types:

- Organic-N low-solubility compounds: These can be further divided into biologically decomposing compounds usually based on urea-aldehyde condensation products, such as urea-formaldehyde (UF), and chemically (mainly) decomposing compounds, such as isobutylidene-diurea (IBDU).
- Fertilizers in which a physical barrier controls the release: The fertilizers can appear as cores or granules coated by hydrophobic polymers or as matrices in which the soluble active material is dispersed in a continuum that restricts the dissolution of the fertilizer. The coated fertilizers can be further divided into fertilizers coated with organic polymer coatings that are either thermoplastic or resins, and fertilizers coated with inorganic materials such as sulphur- or mineral-based coatings.

The materials used for preparation of matrices can also be subdivided into hydrophobic materials such as polyolefines, rubber, etc., and gel-forming polymers (sometimes called “hydrogels”), which are hydrophilic in nature and reduce the dissolution of the soluble fertilizer due to their high water retention (swelling). In general, the matrices are less common in practice than the coated fertilizers. The gel-based matrices are still under development.

- Inorganic low-solubility compounds: Fertilizers such as metal ammonium phosphates (e.g., $Mg NH_4PO_4$), and partially acidulated phosphates rock (PAPR), are typical slow releasing fertilizers of this type.

In the following section, a description of preparation methods and action mechanisms is provided, with emphasis being placed primarily on the CRFs that are common in practice, with main emphasis on coated products.

IV. DESCRIPTION OF CONTROLLED RELEASE FERTILIZERS

A. Coated Fertilizers

1. Fertilizers Coated with Non-Organic Coatings

Sulphur-coated urea, SCU, has been developed at the TVA (Tennessee Valley Authority) laboratories and manufactured commercially for almost 30 years. Its preparation is based on coating preheated urea granules with molten sulphur. Elemental sulphur, a low-cost secondary plant nutrient, was found to be convenient for coating due to its ability to melt at about $156^{\circ}C$, thus enabling spraying molten S over granular urea and possibly on other fertilizers as well. The product contains between 31 to 38% N. After coating the urea with S, a wax sealant is sprayed in order to seal cracks in the coating and reduce the microbial degradation of the S coating (Oertli, 1980; Shaviv, 2001). Finally, a third layer (normally Attapulgit) is added, which serves as a conditioner. The release of N from SCU depends on coating quality. A typical population of SCU granules consists of three types of coatings: damaged coatings with cracks, damaged coatings whose cracks were sealed with wax, and perfect and thick coatings. SCU coated with a damaged coating immediately releases the urea when brought in contact with water. Goertz (1995) called this “catastrophic release” and called the proportion of the urea having an almost perfect and thick coating as “locked-off”. A population of SCU granules may consist of more than one third of damaged granules and about one third of “perfectly coated” granules (Shaviv, 2000, 2001). Therefore, one third or more of the SCU content may be immediately released after being brought in contact with water (denoted sometimes as “burst”), and about one third may be released long after it is needed by the plant (the “lock-off” effect).

2. Polymer Coating of Sulphur-Coated Fertilizers

Due to the relatively poor performance of the common SCU, several CRF manufacturers introduced a modified product in which the sulphur-coated fertilizer is coated by an additional thin layer of an organic polymer (thermoplastic or resin). A polymer-coated SCU is called a PSCU. According to Goertz (1995), the modified PSCU releases in the same way as common polymer-coated CRFs. The additional polymer layer was also intended to improve the attrition resistance of the coated granules. Indeed, the modified products showed a much better release behavior than the SCU. However, in comparing a PSCU with several polymer-coated CRFs, it was found that the PSCU had an initial “burst” of more than 20% of its content and a “tailing” of more than 30% (Shaviv, 2000).

3. Fertilizers Coated with Organic Polymers

Resin-coated fertilizers

Resin-coated fertilizers are those whose coatings are commonly prepared by in-situ polymerization resulting in the formation of a cross-linked, hydrophobic polymer, usually classified also as thermosetting one (degrades upon heating). The two main families of common resins in practical use are the alkyd-type resins (e.g., Osmocote) and polyurethane-like coatings (e.g., Polyon, Plantacote and Multicote) (Trenkel, 1997). The first resin-coated CRF to be commercially produced was the alkyd-type resin-coated fertilizer, Osmocote. It was first produced in California in 1967. The alkyd-type resin is a copolymer of dicyclopentadiene with a glycerol ester (e.g., Shaviv, 2000). The control over nutrient release is achieved by varying the coating composition or thickness. Hauck (1985) described the release from Osmocote as follows: water penetrates the coating through microscopic pores and increases the osmotic pressure within the coated core, thus stretching the coating. The stretching increases the micro-pores, enabling the release of nutrients through them. The alkyd-type coating provides good control over the resin's composition and thickness, making it possible to control the fertilizer's release rate and pattern. Typical formulations contain urea or compound N-P-K (at various ratios) with or without microelements. It can be applied to a large variety of granular or prilled fertilizer products.

The second family of resin coatings is polyurethane-like coatings. In general, the resin is obtained by reacting poly-isocyanates such as di-isocyanate with polyols on the surface of the fertilizer granule (Moore, 1989). According to Moore (1989), this coating distinguishes itself from other resins in that the poly-isocyanate reacts with the fertilizer core as well. In fact most of the organic polymers used for coating granular fertilizers adhere well to the inorganic core, thus forming an attrition-resistant CRF (provided that the coating thickness is large enough). On the contrary, SCU is not attrition-resistant due to the nature of the S coating. The RLCF technology enables coating a large variety of granular and prilled products. It provides good control over release rate and pattern mainly by varying the coating thickness, and to some extent, by changing the resin's composition. The release of nutrients from these products is mainly temperature dependent (Moore, 1989, Shaviv, 2000), while moisture content in the soil, pH, wetting and drying, and soil microbial activity have little effect on the release. This, however, is not unique to this type of coating and it is rather common with polymer coatings (resins and thermoplastic polymers).

Thermoplastic polymer-coated fertilizers

The most widespread technology used for coating granular fertilizers with thermoplastic materials such as polyethylene is by dissolving the coating material in a chlorinated hydrocarbon and spraying it on the granules in a fluidized bed reactor (e.g., Shoji and Gandeza, 1992;). Control over nutrient release is achieved by blending low-permeability polyethylene with a high-permeability polymer, such as ethylene-vinyl-acetate. Gandeza et al. (1991) claimed that improved control over temperature dependence of the release can be obtained by adding a mineral powder to the coating, which controls the Q_{10} factor of the release (Q_{10} is defined as the change in release rate at an increase of 10°C), ranging from 1.8 to 2.55. In fact, values of Q_{10} factors ranging from 1.5 to 2.0 were found by Raban (1994) for several types of common polymer-coated urea fertilizers. The technology described above can be applied to granular and prilled fertilizers. It offers excellent control over release rates and patterns obtained by changing the ratio of polyethylene to ethylene-vinyl-acetate and/or the percentage of added mineral powder.

Several other products with thermoplastic polymers or latex coatings are available. One particular product is prepared by coating urea with EPDM applied in a solvent. The latex coating of urea and other granular compounds distinguishes itself from other coatings by being a water-borne process, whereby a suspension of poly-vinylidene chloride is sprayed on the granules, with no need for recycling organic solvents (e.g., Goertz, 1995, Shaviv, 2000).

V. PREDICTING NUTRIENT RELEASE FROM CRFs

Controlled release fertilizers designed to provide good control over release in soils and to match plant demand are expected to provide high use efficiency (UE) and minimize adverse effects on the environment. Effective utilization and proper management of nutrient application require tools for predicting the release under varying soil and environmental conditions. Release models may also offer the manufacturer or R&D researcher tools to improve the design of CRFs, and provide environmentalists with the means to better assess potential hazards such as leaching or volatilization losses.

Fertilizers coated with hydrophobic materials, especially polymer-coated CRFs, provide reasonable/good control over the release since they are less sensitive to soil conditions. The pattern of temporal release from coated fertilizers ranges from parabolic release (with or without “burst”), through linear release, to sigmoidal release. The linear and sigmoidal patterns can synchronize better with the pattern of nutrient uptake by plants than with the parabolic release (1994; Shaviv; 1996, Shaviv, 2000). The potential of these fertilizers to serve as controlled release nutrient sources has led to a steady and significant increase of their use (Trenkel, 1997).

A. Conceptual Model of Nutrient Release from Coated Fertilizers

An effort was made to describe the different stages involved in the release from coated fertilizers, providing a rather comprehensive description of the processes and factors which affect the release (Shaviv et al., 2003a). The first stage of the release process from a coated CRF is the penetration of water (mainly vapor) through the coating. The vapor condenses on the solid core and dissolves part of it, thus inducing a buildup of internal pressure. At this stage, two pathways are possible. If the internal pressure exceeds the membrane resistance, the coating ruptures and the entire content of the granule is released instantaneously. Goertz (1995) called this sequence the “failure mechanism” or “catastrophic release.” If the membrane resists the internal pressure, the fertilizer is released by diffusion driven by a concentration gradient across the coating, or by mass flow driven by a pressure gradient, or by a combination of the two. This is termed the “diffusion mechanism.” The failure mechanism was typical of fragile, non-elastic coatings, such as sulphur (or modified sulphur) or other inorganic coatings. Diffusion release was observed with polymer-coated fertilizers such as polyurethane-like coatings, alkyd type resins and polyolefins. According to the above description, the failure mechanism yields a stepwise release function for a single granule, while the diffusion mechanism results in a gradual fertilizer release having a sigmoidal shape. The release pattern/shape of a group of granules may however differ from that of an individual granule due to variations in granule and coating properties. A detailed description of the two main mechanisms, diffusion release and failure release, and their mathematical formulations, including the release from a population of granules is provided by Shaviv et al. (2003a, and 2003b). A quantitative description is provided below.

Experiments with polymer-coated urea were performed (Raban, 1994) whereby water penetration and urea release were measured separately. These experiments indicated a release course consisting of three stages : (i) the initial stage during which almost no release is observed (lag period), (ii) the constant release stage, and (iii) the gradual decay of release rate stage. During the lag period, water vapors penetrate into the granule and dissolve part of the fertilizer in the core. The driving force behind this process is the vapor pressure gradient across the coating. The available volume for the condensed vapor is restricted to the voids inside the solid core and those between the core and the coating. The weight of the granule increases slightly, concomitant with the internal pressure.

An increase in granule volume is observed, mainly with the alkyd-type resin. It is assumed that the duration of the lag period is linked to the time needed for the internal voids to fill with water and thus induce good contact of the solution with the inner side of the coating.

Fertilizer release starts when a critical volume of saturated solution is formed inside the granule, which also induces a buildup of pressure. This is the beginning of the second stage, the constant release rate stage. The release rate remains constant as long as the saturated solution in the granule is equilibrated with the solid fertilizer. The constant (saturation) concentration yields a constant driving force for fertilizer transport (i.e., constant concentration gradient or pressure gradient). It was found experimentally that the volume of the granules remains practically constant during this stage, indicating that the volume evacuated by the released fertilizers is occupied by water that continues to enter the granule. Thus, once the fertilizer in the core is dissolved, the concentration of the internal solution decreases (dilution) as the release proceeds, and the driving force for the release decreases accordingly. This is the decay stage, part of which may be too slow (a kind of a moderate “tailing effect”). The above description served as the basis for a detailed mathematical model for the diffusion release mechanism (Shaviv et al., 2003a) and for the release from a population of granules (Shaviv et al., 2003b).

VI. CONTROLLED AND SLOW RELEASE FERTILIZERS IN PRACTICE

The largest consumption is in the US and Canada, where about 2/3 of the total amount are used. European countries and Japan consume the rest fairly equally. In Japan, most of the CRFs are used in agriculture, mainly for growing vegetables, rice and fruits, and only a small proportion is used for turfs and ornamental horticulture. In the US, Canada and Europe, about 90% of the total consumption is used for non-farm purposes (golf courses, nurseries, professional lawns, landscaping); only about 10% is used for agriculture, mainly for vegetables, melons, strawberries, citrus and other fruits. However, the growth rate of CRF use in agriculture is more than double the growth rate in non-farm markets. Trenkel (1997) reports on details of CRF production and consumption in the US, Europe and Japan based on the manufactured products or crop markets.

Most fertilizers used in agriculture are coated CRFs (about 75%), with a clear trend of a steady increase in the use of polymer-coated CRFs at an annual average rate of about 10%. Non-agricultural markets use about equal amounts of coated SRFs/CRFs and organic-N compounds. Here, too, the proportion of coated fertilizers (mainly SCU and PCSU) has increased over the past decade. CRFs that perform better (and are also more expensive) are preferred for nurseries and in agricultural markets. This indicates consumer awareness of the improved agronomic efficiency of coated CRFs over the other SRFs.

Despite continuing technological developments and the commercial availability of several SRFs/CRFs that perform well, their use in agriculture is very limited (Shaviv, 2000). The main reason for their limited use is their high cost, which may be three to ten times higher than a corresponding standard fertilizer. The potential for increased use of CRFs is tremendous in many cases where they have been shown to increase nutrient recovery, sustain high yields, and reduce the adverse environmental impacts associated with nutrient loss. Until about a decade or two ago, the practical evaluation of SRFs was based mainly on common crop or plant features (e.g., crop yield, fruit size/weight, grass color) in comparison to common fertilization practices and application rates (Shaviv, 2000). Only in the last 10 years, when the use of coated CRFs became more common, has more emphasis been placed on synchronizing the release pattern with nutrient demand of specific crops.

VII. EVALUATION AND CHARACTERIZATION OF CRFS

A. Agronomic Benefits Associated with the Use of CRFs

Many of the experiments using CRFs compared similar levels of nutrients supplied by common fertilizers, ignoring the potential to reduce application levels, and still maintain or even increase yield levels. Improved CR products offering “tailor-made” release characteristics and an increased awareness of the importance of matching release rate and pattern with plant demand, have started to motivate agronomists and consumers to adapt a management-oriented approach. Several examples were shown recently for rice (Shoji and Kanno, 1994) and for greenhouse or container-grown plants (Shaviv, 1996;). In these experiments, the application rates of CRFs were reduced in comparison with those of common fertilizers, the yields were maintained or increased, and the losses to the environment were reduced. Trenkel (1997) presents several examples of cost estimates for using CRFs in comparison to common practices for citrus grown in Florida and for rice grown in Japan, where lower rates of nutrients were applied by using CRFs.

B. Environmental Aspects of Using CRFs

An effective assessment of the environmental impact of CRFs must rely on improved knowledge regarding: (i) nutrient release characteristics and mechanisms, (ii) effects of environmental factors (temperature, moisture, aeration, bio-activity, root excreta, soil type, etc.) on the release and NUE, and (iii) plant nutrient demand under different agricultural conditions. Increased attention has recently been paid to a quantitative assessment of the potential to reduce adverse environmental effects by using CRFs (Shoji and Kanno, 1994; Shaviv, 2000). This may be attributed to the significant development and increased utilization of CRFs that perform well, and to the efforts made by governmental authorities and the pressure exerted by “environmental lobbies”.

The environmental impact of coating substances spread into the soil should be considered, particularly with repeated high application rates. Polyolefin coatings are known to have the lowest degradation rates among the three main types used in practice (alkyd resins, polyurethane-like resins and polyolefins). Data for the degradation rates of such materials are scarce, and there is a need to assess whether these polymers may accumulate in soils and pose environmental problems.

C. Characterization of the Controlled Release of Nutrients - Rationale

Characterization of release from a given SRF/CRF is one of the most important steps in evaluating the effectiveness of a given fertilizer. Despite the significant advances reported here, there is still much confusion and lack of information regarding the critical factors affecting release mechanisms and characteristics. In addition, different research and industrial laboratories still use different characterization methods. Trenkel (1997) provides a partial list of methods used by several manufacturers of coated fertilizers to assess the release of different SRFs/CRFs. Tests performed at temperatures ranging from 20⁰C to 60⁰C at varying sampling frequencies are reported. Naturally, UF manufacturers use tests that, by nature, are different from those used for polymer-coated CRFs. In practice, laboratory tests of nutrient release into water account only for the physical processes associated with the release. One should bear in mind that there might be significant differences between release into free water and release into soil or other growth media.

The differences may be attributed to both physical effects (such as reduced diffusion rates in soils, moisture and temperature fluctuations) and chemical effects (pH changes, root excretion) as well as to the action of microbes on bio-degradable materials (UF, sulphur coating, waxes, etc.). This implies that a correlation between laboratory tests and release rates obtained under field conditions is required in order to achieve the highest NUE with the CRF/SRFs. The correlation should be made carefully, taking into account the release mechanisms of the CRF/SRFs and thus the relevant factors affecting the release.

1. Common Characterization Tests

Over the years, efforts have been made by different manufacturers to establish release tests for use as a standardization tool. In most cases, these efforts were directed to serve the immediate interest or convenience of the fertilizer manufacturer/developer (Wilson and Chem, 1988). The TVA promoted the seven-day dissolution test for SCU, where the release of SCU was determined at 100°F after seven days. The test performed at a relatively high temperature appeared to be somewhat of an accelerated test. Yet, in the case of the SCU, most of the initial release (“burst”) is due to imperfect coating, and thus the short-range temperature effect is less significant than for the long-range one or for the release from polymer-coated CRFs at any stage. This test also ignored the SCU “lock-off” effect, providing only limited information regarding the real duration of the “slow release”. Several manufacturers use the criterion of time needed for 80% release of a given nutrient at 21°C as an indicator of the duration of release. Others use a similar test performed at 25°C that refers to 75% of the release (Shoji and Gandeza, 1992). The fact that manufacturers refer to only 75% to 80% of the nutrient is due to the “decay period” characteristic of all membrane-coated CRFs. As long as the membranes do not disintegrate, the last 10 to 20% of the fertilizers are released over a “too long” period, sometimes beyond the window of release desired by the plant. It should be noticed that this differs from the “lock-off” or “tailing” effects observed for SCU (Goertz, 1995), where the release is almost stopped. In any case, a test referring only to duration of 75% or 80% release implies that the user can count mainly on about three quarters of the nutrients during the growth period. It also ignores the possible existence of a “burst,” as shown by Shaviv (1996). This may have severe agronomic and environmental implications when comparing SRFs with a high initial “burst” (such as SCU or UF), or polymer-coated fertilizers having a large proportion of damaged granules to CRFs that perform well (Shaviv, 2000).

Gandeza et al. (1991) used an empirical expression for the effect of cumulative temperature on the Q_{10} factor of a polyethylene-coated urea fertilizer, enabling the prediction of release under real conditions with varying temperatures. Researchers and agronomists are aware of the temperature effect, but the message should be better implemented in release tests and conveyed as useful information to end-users.

Wilson and Chem (1988) criticized the information presented on the labels of SRFs, stressing the need to specify the content of the water-soluble components in the SRF rather than the total amount. They also drew attention to compound N-P-K SRFs, from which the fractional rate of release of N is greater than that of K, and even more so than the release rate of P. Shoji and Gandeza (1992) demonstrated this phenomenon with polyolefin-coated CRFs. Shaviv (2000) showed this to be a general trend in polymer-coated CRFs used in practice.

2. Towards Improved Characterization and Standardization of CRF/SRFs

Efforts are being made by task forces in the US and Europe to focus on characterization methods of SRFs and CRFs (Trenkel, 1997). The American task force (TF) was formed jointly by the AAPFCO (Association of American Plant Food Control Officials) and the fertilizer industry. The TF proposes a “unified” scheme for rapid determination (about seven days) of release characteristics of CRF/SRFs, regardless of their release mechanism. It applies both to coated fertilizers and organically bound N-compounds such as UF and IBDU (Hall, 1999). The method is used simultaneously in different laboratories in the US, Canada and Europe, and the results of the proposed accelerated test are also correlated both with common tests used in these laboratories and with agronomic results. This is indeed a vital step towards standardization. Yet, it is questionable if the “unified” approach to CRF/SRFs that may be affected so differently by environmental and soil conditions will help remove “the confusion and misunderstanding of terminology and release mechanisms of SRFs” (Hall, 1999). The European TF was established by the CEN (European Committee for Standardization). It initially focused on “a method for the identification and determination of slow release properties of nutrients from coated fertilizers” (CEN/TC290, 1998). These efforts are expected to provide a basis for new official standards and for legislation related to the labelling and definition of CRF/SRFs.

The conceptual description of the release and the mathematical models described above provides tools for a systematic approach to determine release characteristics and to evaluate the release mechanism of coated CRFs. This is the basis for the scheme proposed by Shaviv (2000) that distinguishes between failure and diffusion release mechanisms. For the failure mechanism, it is suggested to proceed at least through the steps denoted “failure 1” and “failure 2” in Figure 5 to obtain minimal, essential information in order to use the CRF effectively. Once the mechanism and release characteristics are known, a further evaluation of the main factors affecting nutrient release from coated CRFs may be made. This could include information about the mean granule diameter and its size distribution, the mean coating thickness and its distribution, water and solute permeability through the coating, fertilizer density, and nutrient solubility (Shaviv et al., 2003a). The information should be useful for technologists dealing with designing or improving CRFs or professionals dealing with better management of CRF application.

In addition to the use of laboratory tests it is advisable to test/evaluate the performance of CRFs in pot or container experiments, which are relevant to their most common utilization in practice (nurseries, greenhouses). An efficient way to evaluate performance under field conditions is to use lysimeters, which are well designed to mimic such conditions allowing good account of nutrient balance (particularly N), losses of the environment and proper evaluation of plant effects.

VIII. THINGS TO BE RESOLVED IN THE FUTURE

Several issues related to better NUE and a more environmentally friendly utilization of CRFs deserve greater attention and deeper insights. , Below are listed some of the more important issues to be dealt with in the near future:

- Improvement and utilization of advanced technologies and development of new concepts for preparing more cost-effective CRFs.
- Improved understanding of the mechanisms controlling release rate and pattern, and the main environmental factors (temperature, moisture, micro-organisms, acidity, soil type, etc.) that affect them.
- Improved assessment of expected benefits to the environment by using CRFs.

- Improved quantification of the economic advantages resulting from reduced losses of nutrients and savings in labor costs.
- Improved assessment of economic benefits expected from reduced osmotic stress and specific toxicity as a result of synchronizing nutrient supply (release) with plant demand.
- Standardization of tests for characterizing the release performance of SRF/CRFs in order to improve a user's decision-making process, industrial quality control, and to assist legislation efforts.
- Utilization of mechanistic-mathematical models for predicting release of nutrients under laboratory and field conditions, and as a design tool for technologists.
- Exposing users to this knowledge to help them choose SRF/CRFs professionally and on quantitative basis.

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