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Release Mechanisms for Slow- and Controlled-release Fertilizers and Strategies for Their Use in Vegetable Production

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SUMMARY. Fertilizer material costs, particularly nitrogen (N), have increased substantially over the past 5 years. Increased costs, along with increased awareness of the impact of fertilizer leaching on the environment in humid regions, have increased interest in use of slow-release fertilizer (SRF) or controlled-release fertilizer (CRF) materials. The goals of SRF and CRF use are that no nutrient should be limiting for crop uptake, there should be improved nutrient uptake efficiency, and nutrient-leaching potential should be reduced. These considerations are particularly important for crops grown on sandy soils with relatively low nutrient and water holding capacities. Release rates of biodegradable, or slow-release materials, such as urea formaldehyde, isobutylidene diurea, and methylene urea are proportional to soil microbial activity and are therefore soil temperature dependent. These materials are N sources and depend on soil biological activity, thus, soil temperature during specific crop growth phenology must be considered and release may be delayed by soil fumigation. Whereas CRFs depend on diffusion through coatings and not biodegradation, both are soil moisture and temperature dependent. Examples of coated materials are sulfur-coated urea, polymer-coated urea, and polymer/sulfur-coated urea. The advantage of these materials is that leachable fertilizer elements other than N can be incorporated within the coating. However, this comes at an increased cost. The use of any single or combination of these materials depends on time of year, the length of crop cycle and crop nutrient demand patterns, and the use of soil fumigants.

Nitrogen is consumed by crop plants in large quantities. However, N in nitrate form is also highly leachable, particularly in sandy soils, and can contaminate groundwater (Hartz, 2006; Jackson et al., 1994; Sanchez, 2000). Therefore, on soils with limited nutrient retention capacities, it is desirable to increase the number of split applications of N fertilizers to reduce leaching potential or to use products designed to release N over time. Nutrients from slow-release fertilizer (SRF) and controlled-release fertilizer (CRF; referred to collectively as S/CRF) release N, and in some cases, other fertilizer elements, at different rates and through different mechanisms (Sartain et al., 2004). These release mechanisms will be discussed below. Available since the 1950s, most S/CRF consumption was by nonfarm or specialty markets (i.e., nurseries, home lawns,

recreational areas, and golf courses). The primary reason for the lack of use of S/CRF materials in agriculture has been the cost per unit of N (Simonne and Hutchinson, 2005; Trenkel, 1997).

Vegetable production in the United States often is located upstream and/or adjacent to large tracts of land set aside for water management, ecosystem restoration, or urban development. These lands are often located near densely populated urban areas with citizens highly engaged in water and nutrient management issues. Because vegetable growers are being asked to reduce potential impacts of agricultural production on water quality through implementation of best management practices (BMPs), there is a need to better manage fertilizer inputs. Despite their present cost, S/CRFs have the potential to increase fertilizer efficiency and reduce N loss to the environment. There are several manufacturers of S/CRFs, and each manufacturer has one or more formulations. Some S/CRF products have already been thoroughly tested, and targeted products have been developed for use in high-value

perennial plantings such as citrus (*Citrus* spp.) (Obreza and Rouse, 1993, 2006). S/CRF technology is currently being widely investigated in vegetable crops, but it remains to be seen whether this technology is appropriate for short duration crops with lower per-unit value than citrus, landscape plants, or greenhouse-grown products.

S/CRF materials have been shown to increase nutrient use efficiencies and reduce environmental impact of agricultural production (Sartain et al., 2004). Increased pressure from environmental groups and state regulators for the adoption of BMPs have led to increased use of S/CRF. However, consumption of these fertilizers remains a relatively small portion of total agricultural use in the United States (Simonne and Hutchinson, 2005). This is particularly true for short-term crops such as vegetables. S/CRF technologies are classified by their release mechanism. Therefore, understanding these mechanisms in terms of nutrient availability to the target crop plant is critical to the choosing the proper material for the crop to be grown.

Most SRF are chemical compounds that are only slightly soluble in water or are slowly broken down by microbial action (Sartain et al., 2004). On the other hand, CRF are made of soluble fertilizers coated with materials that limit exposure of the soluble material to water and/or release of the resulting nutrient solution by diffusion. Thus, the rate of nutrient liberation from SRF is related to their water solubility, microbiological degradation, and chemical hydrolysis. Important factors affecting degradation and hydrolysis are particle size, soil temperature, and microbial activity. Particle size relates to increased surface area for chemical and biological degradation in reduced particle size. Release rates of CRF products, on the other hand, are a function of temperature and soil water content. The following discussion will concentrate on the release mechanisms of various categories of S/CRF materials and how their release mechanisms influence use in vegetable production.

Organic materials

SRF materials are limited to those released by microbial decomposition

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or chemical hydrolysis. Examples of materials released as a result of microbial decomposition are products not normally thought of as slow-release materials; they are manures, composts, and biosolids. These products release nutrients through mineralization of organic matter, and are impacted by soil temperature and moisture content. The greater the soil temperature and soil moisture, the greater the nutrient availability; thus, these products are most effective in warmer weather (Shaviv and Mikkelsen, 1993). Soil fumigation impacts the release rate in that fumigation reduces populations of bacteria required for mineralization. Mineralization rate will increase once bacterial populations have been restored.

Slow-release materials

Two manufactured SRF materials that require microbial degradation are ureaformaldehyde (UF) and methylene urea (MU). A typical UF contains $\approx 38\%$ N with about 30% of total N being water soluble. This material is now available in solutions with very low-molecular-weight polymers and unreacted urea. Methylene ureas are $\approx 40\%$ N with 60% of the total N soluble in water. Because of the increased proportion of soluble N, MUs are not as adversely affected by cool weather or soil fumigation compared with UFs (Sartain et al., 2004). Variants of MU are methylene diurea (MDU) and dimethylene triurea (DMTU). Total N content of these polymers is above 40%, with generally as much as 75% being water-soluble N.

The conversion of UF and MU reaction products to plant-available N is a multistep process, involving dissolution and decomposition. Materials are slow to enter the soil solution by virtue of their low solubility (Shaviv and Mikkelsen, 1993). Longer-polymer-chain products are less soluble than shorter chains and take longer to become available to the plants. Once in the soil solution, UFs and MUs are converted to plant-available N through microbial decomposition or hydrolysis (Shoji and Kanno, 1994). Microbial decomposition is the primary mechanism of N release, with the carbon in the polymer providing the site for microbial activity. Environmental factors that affect soil microbial activity also affect the N availability (e.g., soil temperature,

moisture, pH, and oxygen content) of these products.

The last category of SRF products is those products that are reaction products of urea and aldehydes. N becomes available to plants through hydrolysis and is accelerated by low pH and high soil temperatures (Shaviv and Mikkelsen, 1993). Because the release is not microbe dependent, it can become available at low temperatures; thus, it is one of the preferred products for cool-season application. An example of this category of SRF is isobutyridene diurea (IBDU), although others are marketed.

Controlled-release materials

The second major group of materials is the coated or CRFs. The term "coated fertilizers" is also used for products with a soluble-fertilizer core covered with a water-insoluble coating. The coating limits or controls the rate of water penetration to the soluble fertilizer core, and, in some products, controls the release rate of the solubilized fertilizer from within the granule to the soil. The three categories of coated fertilizers are based on the coating material and include sulfur, polymer, and both sulfur and polymer coatings. These products are now the fastest growing sector of the S/CRF market (Simonne and Hutchinson, 2005).

Sulfur was chosen as a coating material for sulfur-coated urea (SCU) because of its low water solubility, relative low cost, and its value as a secondary nutrient. The mechanism of N release for SCU is by water penetration through micropores and imperfections in the coating. This is followed by a rapid release of dissolved urea from the core of the particle. When wax sealants are used, a dual-release mechanism is created. Microbes in the soil must attack the sealant to reveal the imperfections in the sulfur coating. Because microbial populations vary with temperature, the release properties of the wax-sealed SCU are also temperature dependent (Sartain et al., 2004). The release rate of SCU is directly affected by the coating thickness. Particles with thicker sulfur coatings have fewer imperfections compared with lighter sulfur-coated materials.

Polymer-coated fertilizers represent the most technically advanced state of the art in terms of controlling

product longevity and increasing nutrient use efficiency. Because most polymer-coated products release by diffusion through a semi-impermeable membrane, the rate of release can be altered by composition of the coating and coating thickness. Coated substrates can consist of urea alone or a complete fertilizer containing N, phosphorus, and potassium. Water vapor penetrates the resin coating and dissolves the water-soluble fertilizer core. The dissolved nutrients then diffuse through the coating into the soil. The release patterns are much more linear than SCU technology. Soil temperature influences the rate of diffusion, therefore having the greatest influence on fertilizer release rate. Release periods of these materials vary greatly depending on coating material and thickness, and ranges from 3 to 16 months.

Strategies for use of SRF and CRF

CRFs have been used on agronomic crops (Shoji et al., 2001; Wen et al., 2001) and perennial fruit crops (Hanson and Retamales, 1992; Obreza and Rouse, 2006). Improved growth and yields with CRF compared with soluble fertilizers have been documented on potato (*Solanum tuberosum*) (Hutchinson et al., 2003; Kang and Han, 2005; Pack et al., 2006; Zvomuya et al., 2003) and onion (*Allium cepa*) (Drost et al., 2002). Effects included greater total and marketable yields. The effect of CRF on tomato (*Solanum lycopersicum*) and peppers (*Capsicum annuum*) has been mixed, with reduced and improved yields compared with soluble fertilizers (Csizinszky, 1994).

Reduction in soil microbial populations by fumigants for reduction in weeds and soil-borne insects and diseases is the greatest impediment to the use of some SRF products. Reduction of soil microbial populations can delay fertilizer release by 6 to 8 weeks (Shoji and Kanno, 1994). Therefore, MU, UF, and other SCU products are of limited applicability for relatively short-term vegetable crops where soil fumigation is an accepted practice. However, nutrient release of CRFs is not reduced in fumigated soils because they do not depend on soil microorganisms for release. Soil temperature and moisture influence nutrient release rates of

most S/CRFs, and cool season crops or crops grown on dry soils would be poor candidates for S/CRFs. Fertilizers with nutrients supplied in soluble and controlled-released forms can be developed to match the nutrient demand of short-season vegetable crops and provide adequate nutrition throughout the cropping cycle (Simonne and Hutchinson, 2005).

Conclusions

S/CRF products offer agricultural producers the opportunity to increase nutrient use efficiency, particularly in soils with low cation exchange capacity. However, soil fumigation, temperatures, and moisture content must be taken into consideration when choosing the fertilizer material for the crop. Controlled-release products chosen with release rates that match nutrient demand of vegetable crops should provide adequate nutrition through the season.

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