Description of Enhanced-Efficiency Fertilizers for Use in Vegetable Production[1]

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Nutrient losses from the soil in cultivated fields may reduce yields and cause environmental impacts, which are of concern for growers, environmentalists, and legislators. For example, soluble fertilizer (SF) nitrogen (N) recovery of seepage- and drip-irrigated tomatoes ranged from 61% to 96% and from 36% to 74%, respectively (Scholberg 1996). Thus, in response to the Federal Clean Water Act of 1972 and the Florida Restoration Act of 1999, a series of best management practices (BMPs) was implemented to improve surface and ground water quality (Bartnick et al. 2005). BMPs are cultural practices that, when implemented as a plan, help reduce the environmental impact of production while maintaining yield and quality. One of these BMPs includes the use of controlled-release fertilizer (CRF), which is an enhanced-efficiency fertilizer (EEF). This publication describes the common EEFs and the factors affecting their use in Florida vegetable production.

Enhanced-efficiency fertilizers

EEFs increase nutrient use efficiency by maintaining nutrients in the root zone, increasing the availability of nutrients to plants, and decreasing nutrient losses to the environment (Slater 2010). Although changes in cultural practices may increase fertilizer use efficiency, these practices cannot completely suppress the loss of N to the environment. In circumstances with a high risk of N losses, EEF such as slow-release fertilizers (SRFs), CRFs, and stabilized fertilizers may reduce this risk (Chen and Hutchinson 2008). EEF types and the factors affecting their performance are described below.

1. Slow-release fertilizers

SRFs contain N in a low-soluble, plant-unavailable form that usually requires microbial degradation to release plant-available N. Thus N release is slower than conventional soluble fertilizers, but the release rate, pattern, and duration are not well-controlled compared to CRFs. The two most common slow-release mechanisms include materials of low solubility, such as isobutylidene diurea (IBDU), and biologically decomposable, low-solubility materials, such as urea-formaldehyde (UF) (Ni et al. 2010; Trenkel 2010). Several research studies have been conducted in vegetable crops using SRF with mixed results (Csizinszky 1989; Csizinszky et al. 1992; Ozores-Hampton 2009). Since the N release duration is less controlled compared to CRFs, N release of longer than the season length may result, which is a major drawback to SRFs. In fertility programs that include SRF, these fertilizers often constitute less than 30% of the total N, though this amount may vary widely.

1A. COMMON TYPES OF SLOW-RELEASE FERTILIZERS

Urea-Formaldehyde (UF) and Methylene-Urea (MU): These SRFs are condensation products of urea and formaldehyde in a reaction that includes water, sulfuric acid, sodium hydroxide, and surfactants. This reaction results

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in chains of alternating urea and methylene molecules in varying lengths. The chain length may be selected for during the manufacturing process by controlling the reaction time, pH, temperature, and amount of each component in the reaction (McVey n.d.). UF and MU differ in molecule chain length, the amount of unreacted urea, and the activity index. Table 1 provides a description of activity index and terms found on a UF/MU label.

Urea-Formaldehyde (UF): Among the manufactured SRF and CRF, UF was the first. Patented during 1924 in Germany, it still remains an important SRF (Trenkel 2010). UF contains at minimum 35% cold-water insoluble N and 38% total N. During the manufacturing process of UF, the formaldehyde is transformed into methylene (McVey n.d.). Soil microorganisms break down UF into plant-available N; thus, the mineralization of UF will be affected by microbial activity (Alexander and Helm 2006; Dave and Mehta 1999).

Figure 1. Urea-formaldehyde slow-release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

Methylene-urea (MU): MU contains 40% N in which 60% of the total N is water soluble (Morgan et al. 2009). Varying MU chain lengths are selected for during production (Koivunen et al. 2003). Lower soluble MUs have longer chain lengths and higher slow-release characteristics. Soil temperature and microbial activity are important components of MU degradation (Morgan et al. 2009).

Isobutylidene diurea (IBDU)—31% N: IBDU is the condensation product of isobutyraldehyde (a liquid) with urea, which results in a single oligomer (a polymer whose molecules consist of relatively few repeating units) of low solubility. In contrast to UF or MU that depends on biological degradation for N release, the release pattern of IBDU is dependent on chemical dissolution (IBDU is hydrolyzed to urea in the presence of water). Thus IBDU release rate is influenced by particle size and less influenced by environmental variations compared to MU and UF (Miner et al. 1978; Trenkel 1997).

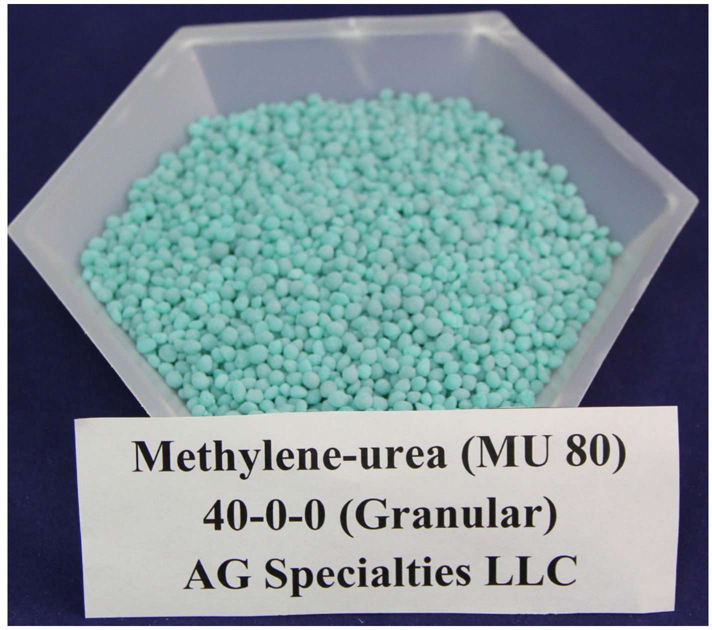

Figure 2. Methylene-urea slow release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

Crotonylidene diurea (CDU)—32.5% N: Crotonylidene diurea (CDU) is produced by the reaction of urea and acetic aldehyde catalyzed by acid. When CDU is placed in the soil, it is degraded into urea and crotonaldehyde through hydrolysis and biological activity. Similar to IBDU, the N release rate of CDU is influenced by particle size; the larger the particles, the slower the release rate (Trenkel 1997).

Urea-triazone (UT)—28% N: UT is the reaction product of urea, formaldehyde, and ammonia, which produces uniform, N-containing rings that must be degraded to release plant-available N (Clapp and Parham 1991). The resulting liquid SRF contains 7.8% free urea and 20.2% slow release N that may be foliar- or soil-applied, including through fertigation. UT should not be applied with ammonium-based N fertilizers, due to the risk of ammonia volatilization, or with ferrous iron fertilizers, due to the risk of iron oxidation to a plant-unavailable form (Liu and Williamson 2013).

1B. FACTORS AFFECTING NUTRIENT RELEASE FROM SLOW-RELEASE FERTILIZERS

Soil microbes degrade UF, MU, and UT into urea and then into ammonium (NH_4^+), providing plant-available N, whereas soil moisture causes dissolution of IBDU and CDU (Clapp and Parham 1991; Fuller and Clark 1947; Morgan et al. 2009; Trenkle 2010). Therefore, factors affecting soil microbes and hydrolysis, which are often the same, affect SRF degradation. Increasing and decreasing moisture and temperature will increase and decrease SRF nitrification, though an optimum soil-temperature range for microbe activity is between 67˚F to 74˚F (Swift 2012). Soil microbes slow their activity at low and high soil-moisture contents (permanent wilting or flooded conditions) and extreme soil temperatures (<40 °F and >95°F). UF and MU are nitrified at a greater rate at pH 6 compared to 5 or 7. Thus a soil pH that affects soil microbe activity will also affect N release. In the presence of phosphorous (P) and potassium (K), MU and UF were nitrified at a greater rate compared to UF alone (Kralovec and Morgan 1954). High soluble salts and soil incorporation will also affect SRF N release by affecting microorganisms. In all SRFs, fertilizer granule size affects SRF nitrification due to surface area. For instance, one pound of large-particle fertilizer will contain less surface area and release N more slowly compared to one pound of small-particle fertilizers.

2. Controlled-release fertilizer

No official differences between CRF and SRF are recognized by the American Association of Plant Food Control Officials (AAPFCO), though the term CRF is used to represent SRFs occluded in a coating. This coating may be composed of polymer, resin, sulfur, or both sulfur and polymer coatings. CRF nutrient release duration is controlled by temperature, coating thickness, and coating composition, though many other factors influence release (Carson and Ozores-Hampton 2013). Thus the term CRF is suitable terminology, because factors affecting nutrient release rate, pattern, and duration are recognized and controlled during the manufacturing process to design CRFs of specific release durations (Shaviv 2001). Ideally, the release pattern and duration will match crop N uptake, though this is difficult to accomplish due to the effect of temperature on nutrient release (Lammel 2005). The sigmoidal nutrient release pattern of CRF begins with a lag period while water is imbibed into the CRF, then shows a constant rate of release at a given temperature that slows after a given amount of time. The slow phase after the constant or linear nutrient-release period is known as the decay phase (Figure 3).

2A. COMMON TYPES OF CONTROLLED-RELEASE FERTILIZERS (TABLE 2)

Sulfur-coated urea—30% to 40% N: Sulfur coated urea (SCU) fertilizer was developed by the Tennessee Valley Authority (TVA) during the 1960s. Granular urea is coated with several layers of molten sulfur and a soft wax coating to seal cracks and blemishes that may occur as the sulfur cools. The wax coating also protects the brittle sulfur coating during handling (Booze and Schmidt 1997). The SCU fertilizer normally consists of 30% to 40% N, 14% S, 2.1% sealant, and 2.5% conditioner. The S and wax coatings slowly degrade through microbial, chemical, and physical processes, which open cracks or holes through which nutrients may diffuse (Figure 3) (Trenkel 1997). Once diffusive release is complete, coatings may be found in the soil as open or broken spheres. SCU is subject to two release problems: catastrophic-type release and lock-off or non-release. The prill may be cracked or broken, thereby releasing all of its content at once, which is called catastrophic release. In the case of lock-off, whole SCU prills may be found with none of their contents released (Trenkel 1997).

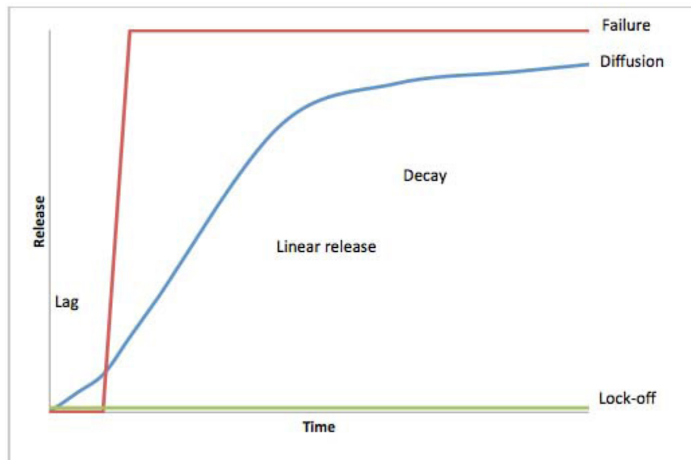

Figure 3. Release from an individual controlled-release fertilizer prill: diffusive release (blue), catastrophic failure (red), and lock-off (green).

Polymer/resin-coated fertilizers—18% to 44% N: Polymer coatings may be manufactured as semipermeable or impermeable membranes with small pores through which nutrients diffuse. Crop nutrients such as N, P, K, micronutrients, and combinations thereof may be coated, though it should be noted that smooth spherical granules coat with greater uniformity and release with greater predictability compared to angular fertilizers. Many coatings can be used in polymer CRFs including polyolefine, polyethylene, ethylene-vinyl-acetate, polyesters, urea formaldehyde resin, alkyd-type resins, and polyurethane-like resins (Carson and Ozores-Hampton 2013; Trenkle 2010). For example, Osmocote (Everris Inc., Dublin, OH) is a CRF with an alkyd-resin coating. When the prills come in contact with moisture, the pores in the resin coating allow water to diffuse into the core, dissolving the water-soluble compounds inside. This increases the osmotic pressure and causes the coating to stretch and the pore size to increase, which allows the nutrients to diffuse back out through the pore (Booze and Schmidt 1997; Trenkel 2010). Since nutrient release from

CRFs is not greatly affected by soil properties—such as microbial activity, redox potential, pH-value, and soil texture—nutrient release may be predicted based on time and temperature (Carson and Ozores-Hampton 2013; Trenkel 1997). This is the leak-type release as fertilizer moves out of the prill slowly. Once release is complete, prills may be found in the soil as intact spheres, full of water.

Figure 4. Resin-coated, controlled-release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

Figure 5. Polymer-coated, controlled-release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

Polymer sulfur hybrid coated urea (PSCU)—37% to 43% N: Due to comparatively poor performance of SCU, several CRF manufacturers added a thin polymer coating to improve function (Shaviv 2001). Polymer-sulfur-coated fertilizer containing N, P, or K may be found, but the vast majority contains urea. PSCU is SF coated with sulfur, then coated with a polymeric membrane, which improves the abrasion resistance of the coated granules. The basis for this hybrid coating is to merge the control-release benefits of polymer coatings and the lower cost of the SCU. The modified PSCU releases nutrients in the same manner as polymer-coated fertilizers and shows an improved release behavior compared to the SCU (Trenkel 1997).

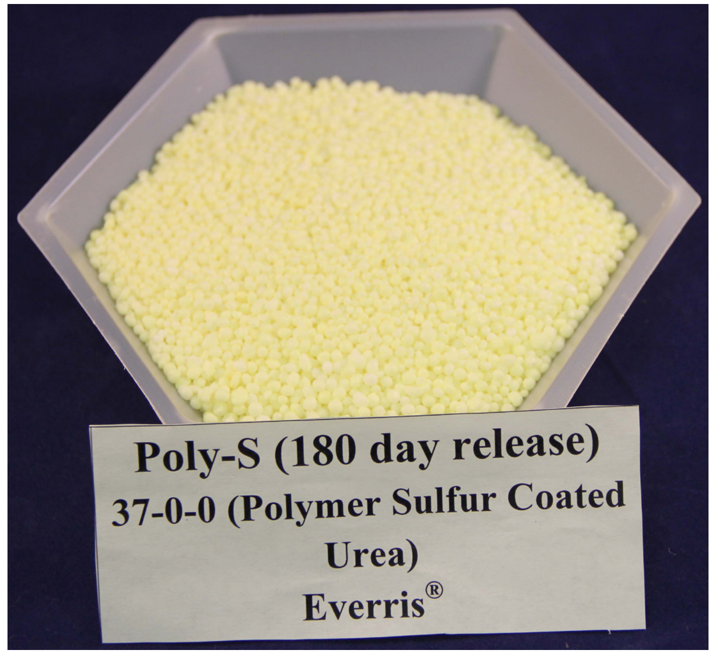

Figure 6. Polymer-sulfur–coated, controlled-release fertilizer.
Credits: Monica Ozores-Hampton, UF/IFAS

2B. FACTORS AFFECTING NUTRIENT RELEASE FROM CONTROL RELEASE FERTILIZERS

Prior to field application, CRF nutrient release may be influenced by management, such as storage, improper handling, and transportation (Shaviv 2001, 2005). Controlled-release fertilizers may imbibe water and release nutrients when stored in high-humidity environments or may become damaged by rough handling. Some manufactures of PSCU require distributors to pass a handling test to ensure that the CRF is handled in a manner that will not cause physical damage.

Soil conditions such as temperature (including thawing and freezing), moisture content, and osmotic potential may influence N release (Carson et al. 2013; Carson and Ozores-Hampton 2013). A reliable understanding of the environmental factors influencing CRF nutrient release allows for use with highest efficiency. In general, nutrient release from CRF is positively correlated with soil temperature and moisture (increases or decreases in soil temperature or moisture result in increases or decreases in nutrient release) (Carson and Ozores-Hampton 2013). Manufacturers of CRFs test nutrient-release duration at a particular temperature (e.g., Agrium Advanced Technologies, Everris, and

J. R. Simplot [patent previously owned by Florikan ESA] and Chisso-Asahi Fertilizer determine nutrient-release duration at constant temperatures of 68°F, 70°F, and 77°F, respectively) (Agrium Advanced Technologies 2010; Everris 2013; Florikan 2012a, 2012b). Temperatures higher or lower than the temperature stated on the label will shorten or lengthen the release duration, respectively. Thus in a raised bed covered with polyethylene mulch during the fall, when temperatures may reach 104°F, a CRF release duration greater than the season length may be necessary. Sartain (2012) describes Florida law regarding fertilizer labels. CRFs should be incorporated in the bed or soil when possible to limit NH_3 volatilization that may occur with urea-based fertilizers. Furthermore, the moisture content inside the bed or soil will be more uniform than the moisture content on the soil surface; thus CRFs will not be subjected to wetting and drying patterns that slow release and that have been reported in non-incorporated CRFs (Medina et al. 2008). Proper CRF placement in the bottom mix is important in polyethylene-mulched vegetable production (Carson and Ozores-Hampton 2013; Csizinszky 1994). CRFs should not be placed in the hot mix due to elevated osmotic potential and temperature, which decreases and increases CRF nutrient release, respectively, making it less predictable in seepage-irrigated crops. Furthermore, use of CRFs in the top mix resulted in similar or reduced marketable tomato yields compared to SF tomato fertility programs (Csizinszky 1989; Ozores-Hampton et al. 2009)

3. Stabilized fertilizers

Nitrification inhibitors (NI) and urease inhibitors (UI) are products added to fertilizers, which are then referred to as *stabilized fertilizers*. The inhibitors are not actually fertilizers in themselves, but they retard bacteria and enzymatic activity in the soil to maintain fertilizers in a form with reduced probability to move out of the root zone by leaching or gaseous losses. The reduced leaching loss is contingent on a soil cation-exchange capacity sufficient to hold the NH_4^+ ions from leaching. Stabilized fertilizers are not frequently used in vegetable production in Florida. In studies on potato and sweet corn, a lack of response to stabilized fertilizers was found, in part due to the low cation-exchange capacity (Hochmuth and Hanlon 2010, 2011). Furthermore, some crops, such as tomato, are sensitive to the high levels of NH_4^+ that results from use of these fertilizers.

3A. COMMON TYPES OF STABILIZED FERTILIZERS

Nitrification inhibitors: NIs retard bacterial oxidation of NH_4^+ to nitrate (NO_3^-) by *Nitrosomonas* and *Nitrobacter* soil bacteria (Trenkel 2010). The aim of using NIs is to maintain NH_4^+ in the ammoniacal form. Once NH_4^+ becomes NO_3^-, it will be subject to greater leaching and losses due to denitrification in high soil-moisture conditions, which are prevalent in seepage-irrigated vegetable production. A common N stabilizer is dicyandiamid or N-Serve by Dow AgroSciences.

Urease inhibitors: UIs slow the conversion of urea to NH_4^+ by slowing the urease enzyme. Urease hydrolyzes urea in/on the soil, which may volatilize in high soil pH and moisture conditions (Trenkel 1997). Thus UIs are used only in conjunction with urea fertilizer. Slowing the rate of urea hydrolysis by the use of UIs can decrease volatilization losses from surface applications of urea fertilizers. The most common UI in the market is Agrotain by Koch Agronomic Services.

3B. FACTORS AFFECTING STABILIZED FERTILIZER EFFECTIVENESS

The factors affecting NIs include those that affect the stability and mobility of the inhibitor in the soil, such as volatilization, decomposition, and degradation. Soil temperature negatively correlates with inhibitor effectiveness. Higher temperatures will increase the rate of inhibitor and NH_4^+ volatilization, microbial degradation of the inhibitor, and the actions of nitrifying bacteria and urease enzymes (Slangen and Kerkhoff 1984). Placement of stabilized fertilizers in bands will slow the rate of NI loss by slowing inhibitor volatilization, which is controlled by vapor pressure, and by increasing soluble salt concentration that may slow microbial degradation. NIs have greater effectiveness in light soils than in heavy soils. Increasing levels of soil pH and organic matter content will require a greater amount of NI to obtain the similar effects.

4. Enhanced-efficiency fertilizer prices

EEFs provide additional value or benefits to the fertilizer and thus cost more than SFs (Table 3). The price of EEfs varies greatly, depending on the type and technology. Stablized fertilizers are the least expensive EEF, and SRFs have prices similar to or higher than CRFs.

Several EEFs are available for vegetable growers to choose from when developing a fertility program. In Florida, EEFs will be most effective in seasons where N loss from the soil may be high due to factors such as high rainfall, light soil textures, and low soil organic matter content. Understanding and applying the factors affecting EEF performance will help growers obtain the greatest benefit from their use.

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Table 1. Explanation of the fertilizer characteristics for urea formaldehyde (UF) and methylene urea (MU).

Characteristics	Explanation
Total nitrogen	The fertilizer grade typically 38% to 40% for UF and MU.
Cold-water soluble nitrogen (CWSN)	This nitrogen fertilizer fraction is soluble in 71.6°F water and is available to plants immediately or within a few weeks. The CWSN fraction contains unreacted urea, methylene diurea, and dimethylene triurea.
Cold-water insoluble nitrogen (CWIN)	This is the slowly available and unavailable nitrogen fertilizer fraction that is not soluble in 71.6°F water.
Hot-water insoluble nitrogen (HWIN)	This nitrogen fertilizer fraction is not soluble in 212°F water, and may be reported indirectly through back calculation using the activity index. The HWIN may not be available to the plants during the season applied.
Activity index	This represents the slow release portion of the fertilizer that is available over the course of several months and is calculated as: AI = ((%CWIN – %HWIN)/%CWIN) * 100.

Table 2. Manufacturer, trade name, control release fertilizer (CRF) type, coating description, and formulation of different CRFs.

Manufacturer[1]	Trade name	Type of CRF	Coating description	Formulation examples
Agrium, Inc.	ESN	Polymer-coated urea	Flexible micro-thin polymer coating	ESN (44-0-0)
Agrium, Inc.	Polyon	Polymer-coated	Ultra-thin ployurethane coating that uses patented "Reactive Layers Coating"	Polyon NPK (20-6-13), Polyon (41-0-0)
Agrium, Inc.	Duration	Polymer-coated	Micro-thin polymer membrane	Duration (44-0-0), Duration (19-6-13)
Agrium, Inc.	XCU	Polymer/sulfur-coated urea	Urea coated first with polymer and then sulfur and wax	XCU (43-0-0)
Chisso-Asahi Fertilizer Co.	Nutricote	Resin-coated	Resin coating with a special chemical release agent	Nutricote (28-0-0)
Chisso-Asahi Fertilizer Co.	Meister	Resin-coated	Granular urea coated with a polymer composition of natural products, resin, and additives	Meister (21-7-4), Meister (19-5-14)
Everris, Inc.	Osmocote	Resin-coated	Alkyd-resin coating made in a batch process from vegetable oil and resin	Osmocote Classic (8-16-12), Osmocote Plus (16-9-12), Osmocote Pro (17-11-10+2MgO+TE)
Everris, Inc.	Poly-S	Sulfur/polymer- coated urea	Urea coated first with sulfur and then polymer	Poly-S (37-0-0)
Everris, Inc.	Agrocote	Sulfur/polymer- and resin-coated	Either 100% N or K potassium fully coated with polymer/sulfur and resin coatings	Agrocote (39-0-0+11%S), Agrocote (0-0-42+14%S),
Haifa Group	Multicote	Resin-coated	Water-soluble nutrients encapsulated in a polymeric shell	Multicote Agri 4 (34-0-7), Multicote Agri 6 (22-8-13) and (34-0-7), Multicote Agri 8 (34-0-7)
J. R. Simplot	Florikote	Polymer-coated	Dual-layer technology coats the fertilizer with a smooth exterior coating with no breaks	Florikote (12-0-40), Florikote (19-6-13), Florikote (40-0-0)

[1]Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the University of Florida and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

Table 3. Prices of enhanced-efficiency fertilizers for use in vegetable production[1].

Fertilizer	Price ($/ton)
Soluble urea	380 to 560
Soluble potassium nitrate	1,150 to 1,500
Methylene urea	750 to 1,000
Urea-formaldehyde	1,100 to 1,300
IBDU	1,400 to 1,600
Controlled-release urea (sulfur coated)	775 to 875
Controlled-release urea (polymer/sulfur coated)	500 to 1,000
Controlled-release urea (polymer)	700 to 1,500
Controlled-release NPK (polymer)[2]	810 to 2,000
Urease inhibitor	20 to 30[3]
Nitrification inhibitor	4 to 8[3]

[1] Fertilizer prices were obtained from one to three sources between April and May 2014.
[2]Nitrogen = N, phosphorus = P, and potassium = K.
[3]These products are marketed in 2.5 gallon containers. The listed price is in addition to the price of the soluble fertilizer and does not reflect additional application costs that may be associated.