Chapter 3

Controlled-Release Fertilizers as a Means to Reduce Nitrogen Leaching and Runoff in Container-Grown Plant Production

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Additional information is available at the end of the chapter

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Abstract

Container-grown plants refer to plants produced in confined volume filled with substrates. The substrates endogenously have limited nutrients and low water-holding capacity. Plants grown in the containers must be fertilized and watered frequently varying from daily to weekly. Frequent fertilization and irrigation can result in nutrient leaching and/or runoff. Since nitrogen (N) is a key component of the majority of fertilizers, container plant production has been viewed as a source of N leaching and/or runoff. The leaching and runoff, if in large quantities on a year-round basis, could affect surface and ground water quality. Application of controlled-release fertilizers (CRFs) has been reported to have less N leaching than plants fertilized with water-soluble fertilizers (WSFs). However, there are different types of CRFs with different compositions and longevities on the market. Container plants also differ greatly in their growth and development and in N requirement. Thus, production of high-quality container plants with minimum N leaching using CRFs still remains challenging. This article is intended to discuss characteristics of container plant production and N leaching and runoff during production, and to document that CRF application can reduce N leaching and/or runoff. Certain requirements for future development of CRFs are also discussed.

Keywords: container-grown plants, controlled-release fertilizers, nitrogen leaching and runoff, nitrate

1. Introduction

Container-grown plants refer to those grown from seedlings, liners, rooted cuttings or grafted plants in containers or pots filled with substrates to marketable sizes or harvestable stages. Substrates or growing media are comprised of peat, perlite, soil, vermiculate or other organic components in different proportions. Many plants can be produced in containers including floriculture, nursery, fruit and vegetable crops. According to the United States Department of Agriculture (USDA) National Agriculture Statistics Service [1], floriculture crops are ornamental plants without woody stems, such as annual and perennial bedding and garden plants, cut flowers, cut cultivated greenery, potted flowering plants, tropical foliage plants and unfinished propagative material. Nursery crops are finished ornamental plants and trees with woody stems that are used for outdoor landscaping. Nursery crops also include ornamental vines, turfgrass sod and other groundcovers. Fruit and vegetable crops can also be produced in containers. Container fruit crops commonly include apple, blueberry, cherry, citrus, fig, orange, peach, pear and plum trees. Container vegetables include basil, beet, carrot, cucumber, ginger, lettuce, radish, onion, strawberry and tomato.

Container crop production has become increasingly popular over the past 50 years [2, 3]. This is because container plant production has several advantages over traditional field production: (1) container plants are grown in substrates, not in soil, their production does not rely on arable land; (2) container sizes, substrate types and pH, pest, disease, water and nutrient management are easier to control or modify in container plant production than field production [4]; (3) plants grown in containers have a greater fine root mass compared to field-grown plants [5, 6]. Root surface area of holly plants (*Ilex x attenuata* Ashe 'East Palatka') grown in containers increased more than twofold than those grown in ground, and plant leaf dry weight and total top dry weight were 22.5 and 15% greater, respectively, when grown in containers [5]; (4) container plants are more convenient for moving and shipping, allowing more operational flexibility and improving shipping efficiency; (5) containerization allows growers to sell plants throughout the year regardless of soil conditions or plant growth stage, which increases productivity per unit area; (6) container-grown plants exhibit much less transplant shock and higher survival rates after transplanting compared to field-grown plants [7]; (7) plant spacing for containers ranges from 17,300 to 247,000 plants per hectare in nurseries and 99,000–865,000 plants per hectare in greenhouse production compared to 1480–12,360 plants per hectare in field production [2], thus, much more plants are produced per hectare by container production and more profit is made per unit area and (8) container-grown plants can be consolidated to provide space for growing additional plants after inventories are sold. However, such consolidation will not be possible for field-grown plants. More plants per unit area of container-grown crops means higher revenue compared with field production [8].

Currently, approximately 90% of greenhouse, nursery and floriculture crops in the USA are produced in containers [9]. The floriculture and nursery industries are strong and fast-growing sectors of US agriculture. Together, it accounts for a total of $11.7 billion in sales in 2009, a 10.7% increase since 1998. Floriculture and nursery crops comprise almost 30% of the specialty crops grown in the USA [10]. Since floriculture and nursery crops are used largely for decoration of the surrounding environment, they are produced in every state in the USA. The leading floriculture and nursery states are California, Florida, Michigan, Texas and New York [11]. The floriculture and nursery industries generate 170,000 jobs worth $3.78 billion to California's economy [12]. Floriculture and nursery crops are among the largest agricultural commodity groups in Florida. According to the Census of Horticulture Specialties for 2014

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[13], there were over 2069 commercial nursery and greenhouse farms in Florida, with total sales of $1.796 billion, and $3.291 billion in capital assets in land, buildings and equipment.

2. Nitrogen loss during container plant production

The rapid increase in container plant production, however, has been under increasing scrutiny because of potential contamination of surface and/or ground water by nutrient elements, particularly nitrogen (N). In Europe, extremely high NO_3—N concentrations, up to 2000 kg N/ha, were found in soil depth of 100 cm underlying commercial greenhouses [14]. In Connecticut, US, NO_3—N accumulation over 2300 kg/ha was recorded in soil under decades-old greenhouses [15]. A survey conducted in six states in the US such as Alabama, Florida, New Jersey, North Carolina, Ohio and Virginia suggested that the levels of runoff NO_3—N varied from 0.5 to 33 mg/L for container nurseries using controlled-released fertilizers (CRFs) and 0.1–135 mg/L for those using CRFs supplemented with water soluble fertilizers (WSFs) [16]. Also a survey completed from 11 nurseries in southern California showed that media NO_3—N concentrations in runoff exceeded 10 mg/L in most nurseries [17]. NO_3—N in irrigation runoff in a foliage plant production nursery in southern Florida ranged from 41 to 386 mg/L depending on irrigation methods [18].

Nitrate N is also leached from container substrates during crop production. In a container production of *Ilex crenata* Thunb. 'Compacta', Fare et al. [19] reported that the percentage of applied N leached as NO_3—N ranged from 46% when 13-mm irrigation was applied in 3 cycles to 63% when 13-mm irrigation was applied in a single cycle. Broschat [20] investigated N leaching from a container substrate comprised of 50% pine bark, 40% sedge peat and 10% sand and reported 3710 mg of NO_3—N could be leached per container during a 6-month production of *Spathiphyllum* Schott. This could be translated to the annual loss of 666 kg of NO_3—N per hectare. Container production of poinsettia (*Euphorbia pulcherrima* Willd. ex Klotzsch), a potted floriculture crop, fertilized with a solution containing 210 mg/L of N showed that 40 and 60% of applied N was leached from containers when fertigated with leaching fractions of 0.2 and 0.4, respectively (leaching fraction is defined as the volume of leachate divided by the irrigation solution applied) [21]. Production of container azalea (*Rhododendron* L. 'Karen') with a weekly application of N at 250 mg/L could result in the loss of N at 924 kg/ha [22]. Container production of a bedding plant *Impatiens walleriana* Hook. f. by overhead irrigation resulted in 25.6% of the total applied water leaching out of the container and 34% fell between containers, and weekly N concentrations ranged from 137 to 153 mg/L in leachate and 165–256 in runoff water during a 6-week production [23]. In Spain, NO_3—N in leachates of container-grown *Aloe vera* L., *Kalanchoe blossfeldiana* Poelln. and *Gazania splendens* Lem. ranged from 15 to 90 mg/L when plants were watered in 45% of the container capacity using nutrient solutions containing 372 mg/L NO_3—N and different concentrations of sodium.

Nitrate N resulted from leaching and runoff could enter rivers, lakes and estuaries contributing to water eutrophication. N concentrations greater than 0.4 mg/L have been shown to accelerate eutrophication, causing algal blooms [24]. NO_3—N contamination of groundwater is a major human health concern, particularly to infants when nitrate is transformed to nitrite in the digestive system [25, 26]. The nitrite can oxidize the iron in hemoglobin of red blood cells, resulting in the formation of methemoglobin. Because methemoglobin lacks the ability to bind (or release) oxygen, blood will be unable to carry sufficient oxygen to the individual body cells, causing the veins and skin to appear blue. This is a condition known as methemoglobinemia (sometimes referred to as "blue baby syndrome") [27]. Most humans over 1 year of age have the ability to rapidly convert methemoglobin back to oxyhemoglobin. Thus, the total amount of methemoglobin within red blood cells remains low despite relatively high levels of nitrate/nitrite uptake. In infants under 6 months of age, however, the enzyme systems responsible for reducing methemoglobin to oxyhemoglobin are incompletely developed and methemoglobinemia can occur. This also may happen in older individuals who have genetically impaired enzyme systems for metabolizing methemoglobin. Furthermore, prolonged nitrate and nitrite ingestion could increase risks of certain cancers [28].

The US Public Health Service adopted drinking water standards and set the recommended limit for NO_3—N at 10 mg/L in 1962 [29]. This drinking water standard was established to protect the health of infants, children, pregnant women, the elderly and immune-compromised individuals. The potential health hazard for others depends on the individual's reaction to NO_3—N and the total ingestion of NO_3—N and nitrites from all sources. From 1970 to 1992, the US Geological Survey found that 9% of the private wells that were tested exceed the recommended limit of 10 mg/L NO_3—N [30]. The US Environmental Protection Agency (USEPA) [31] has since adopted the 10 mg/L standard as the maximum contaminant level (MCL) for NO_3—N and 1 mg/L for nitrite-N for regulated public water systems. Subsequent reviews of this standard have not resulted in any changes.

Applied N can also be evolved as ammonia (NH_3) or nitrous oxide (N_2O) gases. It was estimated the 10% of manufactured N fertilizers could be volatilized as NH_3 gas [32] and 1% of N applied in inorganic forms was lost to the atmosphere as N_2O [33]. The volatilization of both NH_3 and N_2O are serious environmental concern as NH_3 contributes to photochemical smog [34] and N_2O is a potent greenhouse gas with a global warming potential of 310 times greater than carbon dioxide [35].

3. Methods for reducing N loss

Different strategies and methods have been proposed and used for reducing NO_3—N leaching and runoff during the production of container-grown plants. Chen et al. [36] suggested that approaches to NO_3—N leaching and runoff should take plant species, fertilizer application rates, container substrate and irrigation methods into consideration for developing best management practices (BMPs), which include (1) understanding plant species requirement for N and application of N based on plant need; (2) improving physical and chemical properties of container substrates and increasing their holding capacities for water and nutrients, particularly NO_3—N; (3) using controlled-release fertilizers to reduce NO_3—N leaching; and (4) irrigation system improvement by using either drip irrigation or subirrigation to reduce leaching and runoff.

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The rationales for the solutions in Chen et al. [36] were as follows: (1) plants are generally inefficient in N utilization. It has been well documented that crops directly utilize less than half (rarely more than 40%) of applied N [37]. Moreover, overall N-use efficiency (NUE) declined with increasing N-fertilizer application [38]. However, recommended fertilizer rates for container-grown plants are often much higher than actual plant needs. As shown by Chen et al. [36], N rates for some container-grown crops ranged from 1067 to 2354 kg per hectare per year, which is 10–15 times higher than those recommended for many agronomic field crops. Such high recommendation rates, along with extensive irrigation further enhance N leaching and runoff. In addition, different plant species and even their different cultivars differ in N requirement. Thus, a nursery operation should have different fertilizer programs suited to each species or a group of species [36, 39]. (2) Since the commercialization of container substrates after the World War II, substrate components have been predominantly pine bark, peat, vermiculite and perlite. Components newly introduced are coconut coir and polymer gel [36]. Accumulated research evidence indicates that specific zeolites and biochars have an added adsorption capacity for nutrient elements, including N [36, 40, 41]. Incorporating selected zeolites and/or engineered biochars into substrate formation should improve nutrient holding capacity and reduce nutrient leaching. (3) N is the most abundant element in most fertilizer formulation. This is due to the fact that N is the most important nutrient to plant growth and development and a plant generally absorbs more N than other element. Common N compounds in fertilizer formulations include ammonium (NH_4^+), nitrate (NO_3^-) and urea [$CO-(NH_2)_2$]. Plants can directly absorb NH_4^+ and NO_3^-, but not urea. Urea in soil is hydrolyzed into NH_4^+ by microorganisms. NH_4^+ can also be nitrified by soil bacteria to NO_3^-. Between NH_4^+ and NO_3^-, most plant species prefer NO_3^- over NH_4^+ although a few plant species prefer NH_4^+. Additionally, as an anion, NO_3^- does not bind readily to the predominantly negatively charged soil and substrate colloids. Thus, NO_3^- is highly mobile in soil or substrate. To reduce the mobility of NO_3^-, encapsulated N fertilizers should be a better choice, and this is why CRFs have been developed [42]. (4) As water and fertilizer are interrelated in container plant production, one way to avoid N runoff or leaching into groundwater is to use zero runoff subirrigation [36]. Growers in Florida adopting either ebb-and-flow or capillary mat irrigation reported 20% reduction of fertilizer use and 75% reduction of water consumption in containerized plant production. Another irrigation method, which can achieve minimal runoff and less salt buildup in substrates, is to use surface irrigation systems, but to also capture, retain and recycle the runoff and stormwater within the boundaries of the production facility [43]. This is exemplified by whole greenhouse/nursery recycling system, called the total nursery recycling system. This recycling system includes (1) stormwater and/or irrigation runoff collection, (2) sedimentation, flocculation, filtration and disinfection, if necessary and (3) irrigation. Skimina [44] tested more than 100 species of landscape ornamental plants using this system and found that the range of plant growth response was 73–171% relative to control plants. However, few nurseries have used this total nursery recycle system for the production of greenhouse container plants. Growers were concerned about the feasibility and reliability of the water sources for the production of high-quality plants. As a result, the use of CRFs is considered to be a more convenient method for container plant production, while potentially reducing N leaching and runoff.

4. Controlled-release fertilizers and their applications

Controlled-release fertilizers are granules that are purposely designed to release nutrients in a controlled, delayed manner in synchrony with plant requirements for nutrients. CRFs belong to enhanced-efficiency fertilizers (EEFs), which is defined as "fertilizer products with characteristics that allow increased plant uptake and reduce the potential of nutrient losses to the environment (e.g., gaseous losses, leaching or runoff) when compared to an appropriate reference product" [45]. EEFs include CRFs, slow-release fertilizers (SRFs), stabilized N fertilizers, nitrification inhibitors and urease inhibitors. The terms, CRFs and SRFs, are generally considered analogous. However, Trenkel [42] and Shaviv [46] clearly defined their differences. In SRFs, the pattern of nutrient release is generally unpredictable and remains subject to change by soil type and climatic conditions. In contrary, the pattern, quantity and time of release can be predicted, within limits, for CRFs. This review, as indicated by the title, is intended to focus on CRFs only.

4.1. Common CRFs used in container plant production

Table 1 lists the leading producers and/or suppliers of CRFs including Agrium Inc., Calgary, Alberta, Canada; Chisso Asahi Fertilizer Co., Tokyo, Japan; Everris NA, Inc., a subsidiary of Israel Chemicals Ltds; Haifa Group, Haifa, Israel; Shandong Kingenta, Shandong, China; and J.R. Simplot, Boise, Idaho, US. CRFs produced by Agrium includes those with trade names: ESN, Polyon, Duration and XCU in which urea is coated by polymer. Popular CRFs include Nutricote and Meister are manufactured by Chisso Asahi Fertilizer, and urea is coated by resin. Everris, Inc. produces Agrocote, Osmocote and Poly-S where urea is coated by sulfur/polymer and resin, resin and sulfur and polymer, respectively. Urea in Multicote produced by Haifa Group is coated by resin, and Florikote produced by J.R. Simplot is coated by polymer [47].

Urea is a major N source for formulation of CRFs. Urea is actually the most widely used fertilizer globally because of its high N content (46%). Urea has the lowest transportation costs per unit of N and ease of application [32, 33]. Additionally, urea is highly soluble in water and has much lower risk of causing fertilizer burn to crops. Other N sources used in the formulation of CRFs include ammonium nitrate, ammonium phosphate and potassium nitrate. Sulfur was initially used as a material for coating urea. The Tennessee Valley Authority developed the production process for sulfur-coated urea more than 50 years ago [48] in which preheated urea granules were coated with molten sulfur and wax. The sulfur coating is an impermeable layer which can be slowly degraded through microbial activities and soil chemical and physical processes. The uniformity in coating coverage and thickness of coating determine the speed and effectiveness of urea release. Incompletely coated or cracked prills are immediately amenable to dissolution in soil water and hydrolysis by urease. However, due to its amorphous nature, sulfur alone cannot be used to produce well controlled-release urea. Subsequently, many other materials, such as binders, plasticizers and sealants were evaluated for reducing the immediate burst effect. Some tested materials reduced the burst effect but increased the cost and complexity [48]. As a result, sulfur alone has not been used as a coating agent. If used, it is in combination with some polymers. Polymer coating is a more sophisticated technology, and it consists of a core of soluble nutrients surrounded by a polymer coating. Each coated

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Trade name	Manufacturer	Type of CRFs	Coating materials	Selected commercial products
Agrocote®	Everris, Inc.	Polymer/ resin-coated	Coated with polymer/sulfur and resin coatings	Agrocote® 19-6-12, Agrocote® 39-0-0 + 11% S
Duration®	Agrium, Inc.	Polymer-coated	Clay-coated PCU or micro-thin polymer membrane	Duration®CR, Duration® 44-0-0, Duration® 19-6-13
ESN®	Agrium, Inc.	Polymer-coated urea	Urea is coated with flexible micro-thin polymer	ESN® 44-0-0 (Environmentally smart nitrogen)
Florikote	J.R. Simplot	Polymer-coated	Coated with dual layer technology	Florikote® 40-0-0), Florikote® 12-0-40, Florikote® 19-6-13,
Meister®	Chisso-Asahi Fertilizer Co.	Resin-coated	Granular urea coated with a polymer composition of natural products, resin and additives	Meister® 15-5-15, Meister® 19-5-14
Multicote®	Haifa Group	Resin-coated	Nutrients encapsulated in a polymeric shell	Multicote® Agri 6 22-8-13, Multicote® Agri 6 34-0-7, Multicote® Agri 8 34-0-7
Nutricote®	Chisso-Asahi Fertilizer Co.	Polymer-coated NPK	Polymer coating with a special chemical release agent	Nutricote® NPK 20-7-10
Osmocote®	Everris, Inc.	Organic resin-coated	Granule contains NPK coated with organic resin	Osmocote® Exact, Osmocote® Exact Mini, Osmocote® Pro, Osmocote® Start
Polyon®	Agrium, Inc.	Polymer-coated	Coated with patented "Reactive Layers Coating" (ultra-thin ployurethane coating)	Polyon® 41-0-0, Polyon® NPK 20-6-13
Poly-S®	Everris, Inc.	Polymer-/sulfur-coated urea	Urea coated with sulfur followed by polymer	Poly-S® 37-0-0
TriKote®	Agrium, Inc.	Polymer-/sulfur-coated urea	Urea coated with polymer and sulfur	Trikote® 42-0-0

Table 1. Common controlled-release fertilizers (CRFs) used for production of container-grown plants, vegetables and turfgrass.

particle is known as a prill and nutrient release is controlled by the chemical composition and thickness of the polymer coating. Polymers could be thermosetting, thermoplastic or biodegradable. Some of the common thermoset polymers include urethane resin, epoxy resin, alkyd resin, unsaturated polyester resin, phenol resin, urea resin, melamine resin, phenol resin and silicon resin [49]. Among them, urethane resin is very commonly used [50]. Polyacrylamide is known to reduce soil erosion, and more studies should be conducted for its use in CRFs [46, 51]. Thermoplastic resins are not very commonly used because they are either not soluble in a solvent or make a very viscous solution which is not suitable for spraying; however, polyolefin is used for coating the fertilizer granules. Biodegradable polymers are naturally available and are known to be environmentally friendly because they decompose in bioactive environments and degrade by the enzymatic action of microorganisms, such as bacteria, fungi and algae and their polymer chains may also be broken down by nonenzymatic processes, such as chemical hydrolysis. Commercially, polymers used for coating urea include alkyd resin (Osmocote), polyurethane (Polyon, Multicote and Plantacote) and thermoplastic polymers.

4.2. N release patterns from CRFs

Different models have been proposed for explaining nutrient release patterns of CRFs [45, 52, 53]. It is generally agreed that nutrient release is governed by diffusion mechanisms. Shaviv [46] and Liu [54] proposed a multi-stage diffusion model. According to this model, after application of a coated fertilizer, irrigation water penetrates the coating to condense on the solid fertilizer core followed by partial nutrient dissolution. As osmotic pressure builds within the containment, the granule swells and causes the occurrence of two processes. One could be "catastrophic release". When osmotic pressure surpasses threshold membrane resistance, the coating bursts and the entire core are spontaneously released. This is also referred to as the "failure mechanism". In the second, if the membrane withstands the developing pressure, core fertilizer is thought to be released slowly via diffusion for which the driving force may be a concentration or pressure gradient, or combination thereof called the "diffusion mechanism". The failure mechanism is generally observed in frail coatings (e.g. sulfur or modified sulfur), while polymer coatings (e.g. polyolefin) are expected to exhibit the diffusion release mechanism [48]. Nutrient release from CRFs is generally classified into linear and sigmoidal patterns [42, 55]. In most cases, the energy of activation of the release, EA_{rel}, is calculated on the basis of estimates of the rate of the release (percentage release per day) during the linear period obtained from the release curves [52]. Nutrient release profiles are established in both laboratory and field tests. Laboratory tests include extraction of nutrients at 25, 40 and 100 °C. Field tests include the placement of net bags in the ploughed layer or soil in the actual production soil [42]. Shaviv [56] reported that nutrient release consists of three stages: the initial stage or lag period during which little release is observed; the constant release stage characterized with an increasing release; and the last or mature stage where nutrient release is gradually reduced.

Nitrogen release profiles from CRFs have been studied during container plant production. CRFs are either top dressed (granules are placed on the surface of container substrate) or incorporated (granules are mixed with container substrate before being used for potting). Plants are watered in a specific leaching fraction. Leachates are captured and collected weekly. NO_3—N and NH_4—N in each collected leachate are analyzed. This method is not designed to determine the amount of N released from a CRF over a period of time since N leaching, volatilization and absorption by plants occur simultaneously. It is intended to use the leached N as an indicator for analyzing N release patterns. Leached N can be plotted based on the cumulative N leached (the percentage of N leached in reference of total N applied) at a specific production time or period [57, 58] or simply plotted as concentration of N per container against time (days or weeks) sampled [20, 59]. Depending on the types and formulation of CRFs, container substrate components, production temperature and irrigation volume and frequency, different N release profiles have been reported. Based on the cumulative N leached, the release curves can be generalized to two types: linear [57, 60] and sigmoidal [58] curves. Regardless of N sources in CRFs, NO_3—N is the main N leached, accounting for 80–90%, suggesting that nitrification is active in container substrates [59]. Temperature is a force driving N release from CRFs. Cumulative N leached from both sand and bark substrates incorporated with an Osmocote fertilizer in Florida was much greater than in Ohio [58]. The methods of CRF application affect

N release or loss. More N leached from substrates incorporated with CRFs than those topdressed [59]. Furthermore, substrate moisture is a key factor influencing nutrient release from CRFs.

4.3. CRF application reduces N leaching and runoff in container plant production

Due to their controlled-release characteristics, research has been conducted since the 1960s on the feasibility of the use of CRFs for container plant production [61, 62]. With the increasing availability of CRF types and awareness of N leaching and runoff in the 1980s, research has shifted attention towards N release patterns and N leaching and runoff. **Table 2** presents some representative studies conducted in container-grown ornamental plants, turfgrass, citrus and field crops such as potato. At least six conclusions can be drawn from these studies: (1) the use of CRFs reduces N leaching and/or runoff. Depending on fertilizer types, plant species, application methods and environmental conditions, N in leachates or runoff resulting from CRF application could be approximately 50% less than WSF application. Mello et al. [63] showed that polymer-coated urea reduced N leaching by 64.5% compared to conventional urea in container production of *Lantan camara* L. Broschat [20] showed that 48 and 54% of applied N were leached from a liquid WSF and a granular WSF, respectively, in container production of *Spathiphyllum*, while N leached from two CRFs were 29 and 35%, respectively. N concentrations in runoff derived from container greenhouse production facilities was 43.1 mg/L compared to 4.4 mg/L after the same facilities switched from WSF application to the use of CRFs [64]. (2) CRF application also reduces N leaching in field crop production. NO_3─N in soil water collected by lysimeters 30 cm below potato production bed ranged from 7 to 45.1 mg/L from 39 to 95 days after planting compared to 15.6–172 mg/L fertilized with a WSF [65]. (3) CRFs reduce N_2O emission. Application of urea in turfgrass production resulted in 127–476% more N_2O emission into the atmosphere compared to 45–73% emission by using a CRF [66]. (4) Plant growth or yield resulting from CRF application are equal to or better than those produced by WSF including ornamental plants [16, 20], field crops [65, 67] and turfgrass [66]. (5) CRFs vary in N release and thus N leaching. N concentrations in leachates varied from 60 to 275 mg/L in container production of *Vibrunum* [16] and from 50 to 400 mg/L in other container ornamental plant production [68] due in part to the application of different CRFs. (6) CRF application may improve the rhizosphere microbial community. A study conducted in Japan showed that application of urea-formaldehyde fertilizers to onion bulbs and main roots of sugar beet changed the diversity of the microbial community and the abundances of certain bacterial species [69].

Furthermore, the use of CRFs has been shown to increase nutrient use efficiency and decrease fertilizer application. Trenkel [42] suggested CRFs can potentially decrease fertilizer use by 20–30% of the recommended rate of a conventional fertilizer while obtaining the same yield. In several field trials in Florida, young or non-bearing citrus trees fertilized with CRFs at a 50% of the recommended rate performed equally well compared to 100% of the recommended rate with WSF [70]. The same magnitude of reduction happened in potato production in Florida [71]. Applying CRFs generally reduces salt accumulation, thus minimizing the possibility of leaf burning. The use of CRFs reduces labor costs. Depending on plant species, one application of appropriate amount of CRFs will ensure plant growth until marketable size, while WSF fertilizers have to be applied as fertigation weekly, and sometimes daily.

Plant species	Growing substrate	Fertilizer	N leached or N conc. in leachates/runoff	Plant growth or comments	References
Spathiphyllum spp. Schott	Pine bark/peat/sand	Liquid WSF	48% of applied N leached	No plant dry weigh differences among fertilizer treatments	Broschat [20]
		Dry granular WSF	54% of applied N leached		
		Lightly-coated CRF	29% of applied N leached		
		Heavily-coat CRF	35% of applied N leached		
Lantana camara L.	Krome soil	Urea	N leached from containers fertilized with polymer-coated urea was 64.5% lower than those fertilized with urea	More flowers were produced by plants fertilized with polymer-coated urea than urea	Mello et al. [63]
		Polymer-coated urea			
A leaching column study without plants	Florida sandy soil	Ammonium nitrate	100% of applied N leached	Much less N was leached from Meister than isobutylidene coated urea, and all N was leached from ammonium nitrate.	Wang and Alva [79]
		Isobutylidene diurea	32% of applied N leached		
		Meister polyolefin resin-coated urea	12% of applied N leached		
A leaching column study without plants	Fine sandy soil	Urea	28% of applied N leached	Meister and Osmocote leached much less N than urea	Paramasivam and Alva [80]
		Poly-S	12% of applied N leached		
		Meister polyolefin resin-coated urea	6% of applied N leached		
		Osmocote	5% of applied N leached		
Different foliage and flowering crops	Peat/pine bark/sand	Polymer-coated urea (41-0-0)	23.1 mg/L	Polymer-coat urea provided stable and long-last release of NO_3^-—N and NH_4^+ than the other two. Trikote released more NH_4^+ than the other two. Plant growth was not significantly affect by treatments.	Blythe et al. [81]
		Trikote (42-0-0)	64.9 mg/L		
		Regalite Nitroform (38-0-0)	27.6 mg/L		
Container-grown *Viburnum odoratissimum* Ker-Gawl	Pine bark/peat/sand	Nutricote	275 mg/L	The highest concentrations of NO_3^-N leached from CRFs during a 4.5-month production period. Plant growth indices were not significantly affected by CRFs	Yeager and Cashion [16]
		Osmocote	220 mg/L		
		Prokote Plus	125 mg/L		
		Woodace	60 mg/L		

Plant species	Growing substrate	Fertilizer	N leached or N conc. in leachates/runoff	Plant growth or comments	References
A greenhouse leaching study without plants	Peat/vermiculite/sand	Nutricote 18-6-8	32% of applied N leached	Osmocote 18-6-12, Nutricote, and Woodave exhibited less response to temperature increase and thus less N leaching	Cabrera [59]
		Osmocote 18-6-12	36% of applied N leached		
		Osmocote 18-6-12 FS	51% of applied N leached		
		Osmocote 24-4-8 HN	49% of applied N leached		
		Polyon 25-4-12	45% of applied N leached		
		Prokote Plus 20-3-10	50% of applied N leached		
		Woodave 20-4-11	30% of applied N leached		
Container ornamental plants	Peat/pine bark/sand	Osmocote	50 mg/L	Osmocote steadily release of N	Merhaut et al. [68]
		Polyon	200 mg/L	N release reached a peak on week 9 then stabilized	
		Multicote	400 mg/L	N release reached a peak on week 8 then stabilized	
		Nutricote	400 mg/L	N release reached a peak on week 9 then stabilized	
Potato	Loamy sand	Polymer-coated urea	21.3 kg NO_3—N/ha	Apparent fertilizer N recovery with PCU (65% averaged over four rates) tended to be higher than split-applied soluble N (55%) at equivalent rates	Wilson et al. [67]
		Soluble N	26.9 kg NO_3—N/ha		
Foliage plants	Canadian peat/pine bark/lava rock	WSF	43.1 mg/L in runoff	Plant growth was not affected by switching from a WSF to a CRF	Wilson and Albabo [64]
		CRF	4.4 mg/L in runoff		
Turfgrass	A Timpanogos loam soil	Polymer-coated urea	1.25 mg N_2O—N/m²/h	Polymer-coated urea emitted significantly low amount of N_2O—N	Lemonte et al. [66]
		Urea	2.22 mg N_2O—N/m²/h		

Table 2. Nitrogen lost in leachates, runoff water or emitted into the atmosphere when controlled-release fertilizers (CRFs) only or CRFs with water soluble fertilizers (WSFs) used in crop production or leaching experiments.

4.4. Problems associated with the use of CRFs in container plant production

Several problems are associated with the use of CRFs in production of container-grown plants. Some are due to CRF design and formulation: (1) CRFs cost considerably more to manufacture than conventional fertilizers, thus they are more expensive. For example, one ton of a CRF (44% N) could be $650 compared to one ton of urea (46% N) at $481 [72]. (2) CRFs may not release nutrients based on plant requirements. This could be due to several factors: the formulation of nutrient elements, the permeability and durability of coating materials, plant species and growth stage difference, and inappropriate placement of CRFs, substrate moisture levels and microbial effects as well as production environmental conditions. The N release pattern of CRFs in laboratory tests is generally represented by a sigmoidal curve (**Figure 1**). Such release pattern is appropriate for field-grown crops, such as corn, wheat and tomato, as the lag phase is appropriate for seedling growth or allow transplants to get recovered and established from transplanting shock; log phase is designed for rapidly vegetative growth and the transition from vegetative growth to reproductive growth; and the stationery phase would allow nutrients absorbed or stored in vegetative organs to translocate to reproductive organs. The sigmoidal curve, however, may not be an ideal pattern for producing container-grown plants. Container plants are initiated with rooted cuttings or liners which already have well established root systems. Once the liners are planted in containers, they grow in an accelerated speed and require a steady supply of nutrient without lag phase. Thus, we propose here that CRFs for container-grown plants should have a nutrient release pattern, called "the expected curve for container plants" presented in **Figure 1**, not a sigmoidal curve. Many CRFs were predominantly developed based on the sigmoidal release curve, thus, they may not be ideally suitable for producing container-grown plants. (3) Thus far,

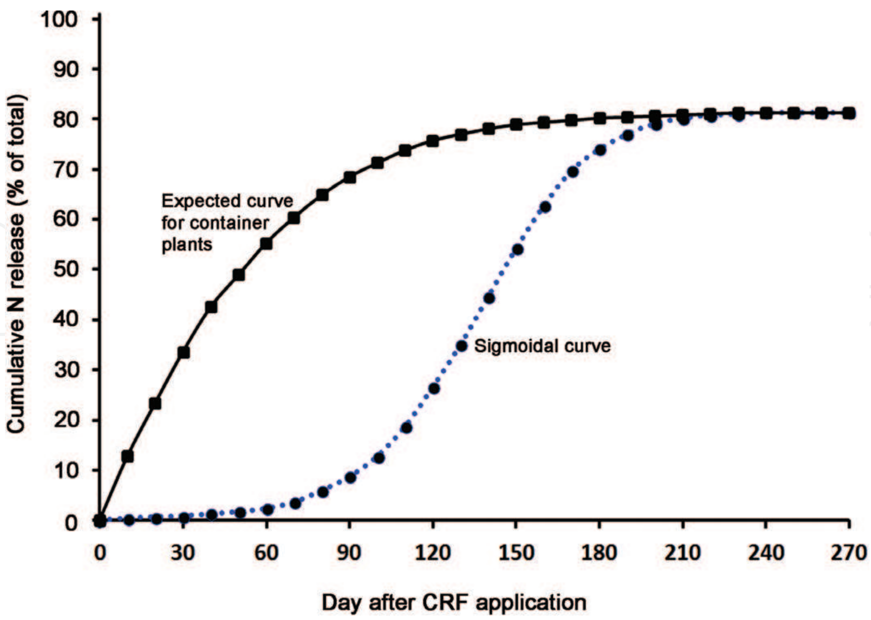

Figure 1. A proposed nutrient release curve versus the commonly preferred sigmoidal curve used for developing controlled-release fertilizers. Controlled-release fertilizer with the proposed curve could be more suitable for production of container-grown plants than those with a sigmoidal curve.

nutrient formulations of few CRFs are developed according to specific groups of plant species in nutrient requirements. Some species have low nutrient requirements. For example, ornamental foliage plants largely originate from the rainforest floor, and they inherently require low light levels and low nutrient supply for slow growth. This group of plants should be fertilized by CRFs that have complete nutrient elements with a rather slower release pattern. CRFs designed for use in subtropics and tropics should be different from those to be used in temperate regions. As shown by Birrenkott et al. [58], the same CRF for growing the same crop released different amount of N in Florida and Ohio.

Other problems with the use of CRFs are related to inappropriate application. The first is the misuse of CRFs. A CRF that is supposed to be used in the Southern USA, but used in the Northern USA, which may cause reduced release of required nutrients; as a result plant growth will be slow. If a CRF designed for container-woody ornamental plants is used for production of annual bedding plants, plant growth may slow down due to limited release of nutrients. The second problem is to apply either too little or too much CRFs. The use of an extra amount is the most common problem in container plant production. This practice not only wastes fertilizers and increases production costs, but also causes N leaching and runoff after excessive irrigation. A large number of plant species are produced in containers, but few species have been studied for N requirements [39]. Those studied were based on a particular substrate in a specific environmental condition. In reality, however, a wide range of substrates have been used in container plant production, and different substrates have different physical and chemical properties. Thus, the established N requirements may not be well suitable for plants to be produced in a different substrate. However, such information does provide reference guides for N application. Nevertheless, the use of extra amount practice must be changed, otherwise, even with the best CRFs available, N leaching and runoff could still occur in container plant production. Third, the methods of placing CRFs significantly affect N release or leaching. Several studies have shown that more N is leached by incorporation of CRFs with substrates, while topdressing had significantly less amount of N leaching [59]. The explanation is that the time for transfer of nutrients through membranes in topdressed CRFs is presumably extended over incorporation due to intermittent drying of the upper growing substrate between irrigation [73].

5. Future development of CRFs

It is certain that CRFs are needed, and the need is increasing. Since the world population keeps growing, it requires more food. Food production requires fertilizers. Meanwhile, container plant production has been growing at a fast pace. The production of container plants also requires fertilizers. As this article documented, container plant production is associated with N leaching and runoff. So far, the volatilization of NH_3 and emission of N_2O have not been well studied in container plant production. This does not mean that the volatilization and emission are not a problem since fertilization is estimated to account for 78% of the total emission of NH_3 and N_2O at the global scale [35]. Therefore, manufacturers should not only pay attention to N leaching but also take emission problems into consideration in the development of CRFs. Future fertilizers must be environmentally friendly and have minimal loss to the air and leaching and/or runoff of N to ground and surface water systems.

The development of CRFs has evolved from a sulfur-coating technology to a polymer-coated technology. With the advance of nanotechnology, future CRFs should integrate nanotechnology components for improving controlled-release characteristics [74]. The future CRFs should be biodegradable; materials used for producing CRFs should be capable of decomposing naturally in most common environmental conditions. Nutrient composition and formulations should be developed based on (1) different groups of plants: annual, perennial and evergreen; (2) the purpose of plant production: growth for fruit, grain or biomass increase (ornamental plants) and/or (3) their inherent needs for nutrients: low, medium and high requirements for major nutrient elements, particularly N. New coating materials that have better permeability and duration as well as biodegradability should be used for coating the nutrient elements. Depending on plant groups and production regions, appropriate coating materials should be used to ensure that nutrients are release largely based on plant requirements. Some natural polymers should be considered including chitosan, xanthan gum, carrageenan, pectin and modified clays [49]. Polymer-clay superabsorbent composites have been reported to be promising as their production costs are low with high water absorbency [75]. Additionally, future CRFs should consider the incorporation of beneficial microbes, such as plant growth promoting bacteria [76] and mycorrhizal fungi [77, 78] to maximize nutrient use efficiency and minimize negative impact on the environment.

6. Conclusion

There is an increasing trend for producing plants in containers worldwide. Container plant production, however, poses mounting concern over N leaching and/or runoff. This is due to the fact that plants are grown in confined substrates that are highly permeable and have low water and nutrient holding capacities, and a large amount of N and water are required for sustaining plant growth. In addition to N leaching and/or runoff, applied N may be volatilized as NH_3 and emitted as N_2O into the atmosphere, contributing to climate changes. This article documents that the use of CRFs can reduce N leaching and runoff and raises the question about NH_3 volatilization and N_2O emission in container plant production. It is firmly believed that the use of CRFs is an effective way of reducing N leaching and runoff and possibly NH_3 volatilization and N_2O emission. With the increase need for food and ornamental plants, the need for fertilizers, particularly CRFs will continuously increase. New environment friendly CRFs should be developed and used for crop and container plant production. On the other hand, since the amount of N lost is a function of fertilizer source, timing, soil infiltration and percolation rate, micropore flow, root density, soil moisture, and precipitation/irrigation rate and intensity, CRFs alone cannot resolve N loss problem. The application of CRFs along with integrated production practices should be carried out for minimizing N loss. Integration includes the application of CRFs based on plant species types and production purpose, irrigation of substrate according to plant need and appropriate methods of applying CRFs to the substrate.

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