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Review

An Overview of Fertilization and Irrigation Management in the Conventional and Certified Organic Production of Vegetable Crops in Florida

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Abstract: The postharvest quality of vegetable crops from conventional and organic production systems depends on pre-harvest factors such as variety genetic potential, fertilization, and irrigation. The five principles of plant nutrition (plants absorb ions, not fertilizers; Leibeig's law of the minimum; nutrient application requires a source, a rate, a placement and a time of application; no correlation exists between total nutrient presence in the soil and availability; and plant nutrient concentration and yield are related) must be followed throughout the crop growth cycle. In certified organic production in the United States, cover crops, manure and composts may be used together with Organic Materials Review Institute–approved fertilizer products. A fertilization program usually includes (1) soil sampling and understanding the recommendation; (2) adjusting pH if necessary; (3) applying preplant fertilizer and developing a schedule for sidedressing or fertigation; (4) using foliar fertilization; (5) monitoring plant nutrient status; and (5) keeping fertilization records. The components of an irrigation schedule are (1) determining a target irrigation volume based on reference evapotranspiration and crop age; (2) adjusting this amount based on soil moisture content; (3) determining the contribution of rainfall; (4) developing a rule for splitting irrigation; and (5) keeping irrigation records. A poorly designed irrigation program can negate the benefits of a sound fertilization program. Challenges encountered in conventional and organic production include predicting nutrient release rates from organic materials, supplying enough N throughout the cropping season, identifying rescue strategies, keeping production costs low, and meeting the additional legal requirements of the food safety and best management practices programs.

Keywords: manure; compost; cover crop; soil testing

1. Introduction

Vegetable crop production today is broadly divided into conventional, sustainable, and organic methods. From an inputs standpoint, "conventional vegetable crop production" usually refers to methods of farming in which the use of synthetic fertilizers, pesticides and herbicides and genetically modified organisms is allowed. "Sustainable" does not have a standard definition, whereas "organic" refers to a system of farming that does not use synthetic chemicals and, instead, mimics natural systems. This may encompass different farm sizes, practices and philosophies that, at their core, reject the use of most synthetic chemicals.

In the United States, both conventional and organic crop production are regulated. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA; U.S. Public Law 92-516, 21 October 1972) and the Clean Water Act (U.S. Public Law 95-217, 27 December 1977) widely regulate the agricultural use of pesticides and fertilizers, respectively. The U.S. organic standards, organic certification, and accreditation, compliance and enforcement are governed by the National Organic Program [1]. The National List of Allowed and Prohibited Substances identifies substances that may or may not be used in certified organic crop production [1].

Vegetable quality at the consumer level depends on four main factors: the genetic potential of the variety used, field production practices used (pre-harvest factors), produce physiological stage at time of harvest, and postharvest handling. This review focuses on water and nutrient management before harvest and covers (1) the principles of plant nutrition; (2) developing irrigation schedules and (3) fertility plans; (4) how to correctly make simple calculations; (5) practices, challenges and successes in the implementation of these plans; and (6) some consequences of water and nutrient deficiencies on vegetable postharvest behavior.

2. The Universal Principles of Plant Nutrition

While the methods and tools to manage fertilization and irrigation are different among all three production systems, the fundamental chemical concepts that drive plant nutrition in the soils and in the plant are universal: pH, oxido-reduction, and solubility [2]. The five fundamental principles of plant nutrition also apply equally in all production systems:

Principle 1. Plants absorb ions, not fertilizers. Essential-element containing ions (and their chemical symbols) commonly absorbed by plants are nitrate (NO_3^-), phosphate ($H_2PO_4^-$ and/or HPO_4^{-2}), sulfate (SO_4^{-2}), borate ($H_2BO_3^-$), chloride (Cl^-), molybdate (MoO_4^-), ammonium (NH_4^+), potassium (K^+), calcium (Ca^{+2}), magnesium (Mg^{+2}), copper II (Cu^{+2}), iron II (Fe^{+2}), manganese II (Mn^{+2}), and zinc II (Zn^{+2}). Chemical forms of the essential elements that are poorly taken up, toxic in small quantities or not physiologically active include nitrite (NO_2^-), nitrogen gas (N_2), phosphite ($H_2PO_3^-$), various oxides and dioxides (CaO, MgO, P_2O_5, K_2O, SO_2), ammonia gas (NH_3), copper I (Cu^+), iron III (Fe^{+3}), manganese I (Mn^+), and zinc I (Zn^+) [3]. Despite some incorrect claims, phosphites, which are registered as the active ingredient of a group of fungicides, are not a source of readily available P as a plant nutrient [4].

Principle 2. The law of limiting factors. The application of Leibeig's law of the minimum to plant nutrition states that crop growth and yield are limited by the essential element in shortest supply. Adding more of any other element (that is therefore not limiting) will not result in a plant response.

Principle 3. The four Rs of nutrient application. Fertilizer recommendations may result in correct nutrient application only when they include a Right fertilizer source, a Right rate (based on field surface or length of rows fertilized), a Right placement or application method (broadcast, modified-broadcast, banded, or injected) and a Right time of application (based on days after emergence or transplanting, or preferably based on the crop growth stage). Hence, the popular discussion of total seasonal rates alone is insufficient to implement a fertility plan.

Principle 4. No correlation exists between total nutrient amount in the soil and availability for uptake by the plant. Soil pH (that controlls the oxidation state, dominant chemical species, and possibly favoring the release of aluminum [2]), cross-precipitation (possibly Ca with P or Ca with S), competition effects (Na with K, P with Al, or Fe with Mn, for example), and constituents of soil organic matter (mostly for N, P and S) may result in reduced availability. The important soil nutrient fraction is the extractable fraction, which is the one recovered by soil extractants during soil testing [5,6]. Principle 5. Leaf nutrient concentration and crop growth/yield are related. Insufficient nutrient supply and concentration in plants may result in deficiency symptoms. Several generic keys are available online to identify nutrient deficiencies in vegetable crops [7–9].

Visual symptoms need to be confirmed with a diagnostic of the crop nutritional status by using tissue analysis [10] or petiole sap testing [11]. With both methods, plant nutrient (content in % or mg/kg (ppm) on a dry weight basis for tissue analysis or in mg/L (ppm) of sap for petiole sap testing) is compared to established sufficiency thresholds. These diagnostic methods are the basis for supplemental fertilizer applications in the Florida Best Management Practices program for vegetable crops [12].

3. Irrigation Scheduling

Most vegetable crops are irrigated with seepage irrigation, overhead irrigation or drip irrigation [13,14]. Scheduling irrigation involves determining when to irrigate and how much to apply. For all irrigation methods, the steps of an irrigation schedule are: (1) determine a target irrigation volume based on reference evapotranspiration (ETo) or Class A Pan evaporation (Ep) and crop age; (2) adjust this amount based on soil moisture content; (3) determine the contribution of rainfall; (4) develop a rule for splitting irrigation; and (5) keep irrigation records [15–17].

Poorly designed irrigation systems, insufficient irrigation system maintenance plans or poor irrigation scheduling practices may negate the benefits of a sound fertility plan. Poorly designed irrigation systems may break, fail, or operate at insufficient pressure. Poorly maintained irrigation systems will result in non-uniform water applications. Excessive water (from irrigation or rainfall) may move soluble nutrients below the root zone, especially in course-textured soils [18].

4. Fertility Plans

The crop nutritional requirement (CNR) is the total amount of nutrients needed to produce a crop. The CNR is supplied by the soil and by fertilization [19]. Hence, the goal of a fertility plan is to ensure that the supply of essential elements does not limit productivity. A fertility plan starts with soil testing and determining the potential contribution of the soil to supplying nutrient needs [20,21]. The difference is typically supplied by combinations of cover crop residues, compost, animal manures, organic amendments, and fertilizers. In certified organic production, cover crops, manure and composts are used together with Organic Materials Review Institute—approved fertilizer products [22].

The components of a fertility plan are: (1) soil test, understand the recommendation and make the correct calculations; (2) lime if necessary; (3) apply organic amendments (cover crop, compost, or manure); (4) incorporate the preplant fertilizer, then sidedress or develop a daily/weekly fertigation schedule, adjusting the amount to the crop growth stage; (5) use foliar fertilization (this practice is recommended for the application of micronutrients to high-pH soils when needed); (6) assess the efficacy of the fertilizer program through leaf sampling or petiole sap analysis; (7) trap residual nutrients at the end of the season with a cover crop; and (8) record the date of application, material, placement and source of all fertilizer used. For practical purposes, the contribution of each nutrient source in the fertility plan may be tabulated to avoid insufficient or excessive nutrient applications (Table 1).

Table 1. Generic blank fertilization worksheet for vegetable crop production.

Nutrient Source [z]	Material (kg/HA [y])	N (kg/HA)	P_2O_5 (kg/HA)	K_2O (kg/HA)
Soil test recommendation	–x–			
Compost				
Cover crop				
Manure				
Soil organic matter decomposition				
Fertilizer needs [x]				
Preplant application				
Sidedress				
Fertigation				
Foliar fertilization [w]				

[z] The nutrient contribution of compost, cover crops and manures depends on the total nutrient content of the material, the method of application (banded *vs.* broadcast) and the mineralization rate. [y] 1 HA = number of linear meters of bed (or row) in one planted hectare at standard bed (or row) spacing. [x] Fertilizer needs = soil test recommendation – compost – cover crop – manure – soil organic decomposition; Fertilizer needs = Preplant application + Sidedress or Fertigation + Foliar fertilization. [w] Recommended to correct micronutrient deficiencies in high-pH soils only. Macronutrients may be injected in the irrigation water when overhead systems are used.

5. Correct and Simple Fertilizer Calculations

All the benefits of soil testing, plant analysis and other cultural practices may be negated by the incorrect calculation of nutrient rates and ensuing fertilizer application rates. Fertilizer calculation rates may be grouped into five types: (1) length of the row in a planted hectare at standard bed spacing [21]; (2) broadcast application rates; (3) modified broadcast or banded application rates; (4) injected rates of liquid fertilizers [23]; (5) fertilizer applications when non-standard bed (or row) spacings are used [24]; and (6) calibration of fertilizer application equipment.

6. Extension Challenges and Successes in Vegetable Production

The mission of the Florida Cooperative Extension Service (FCES) is to provide vegetable growers the latest science-based information they need to solve their water and nutrient management challenges and enable them to do so in an environmentally friendly, economically sound and consumer-safe manner. Growers benefit from the FCES in two main ways: preventive education and diagnostic assistance during crop production (Table 2).

Table 2. Common tools and educational events from the University of Florida (UF/IFAS) available to conventional and organic vegetable producers for improving water and nutrient management on their farms.

Tool	Description
Soil testing	Use representative sample; select appropriate extractant for soil type [25]
Livestock waste testing	Laboratory analysis of a representative animal waste sample includes a test for total Kjeldhal nitrogen (TKN), ammonium (NH_4^+-N), phosphorus (P) and potassium (K), moisture content (%), total solid content (%), total ash (%), and pH. Based on test results, nutrient recommendations for N, P, and K are provided for selected crops [26]
Calculations	Correct conversions of nutrient rates to material rates; adjust total nutrient rates to placement method and mineralization rates; calibrate equipment
Soil moisture measuring device	Note if device measures a soil water tension (tensiometer, gypsum block; granulometric water sensor) or a volumetric water content (Time Domain Reflectometry probes); place correctly in the bed in relation to water source; service and maintain as needed; read daily Multi-depth scanning probes connected to a computer by satellite or a cellular phone line allow for real-time, continuous and remote soil moisture monitoring Weather data and irrigation tools are available on the Florida Automated Weather Network website [27]
Sap testing/leaf analysis	Follow a weekly schedule if possible; compare results to sufficiency ranges; adjust fertilization application accordingly
In-field dye tests	Visualize the movement and distribution of water in the soil relative to the rooting zone
Water and nutrient management virtual field day	Watch short videos on how to conduct on-farm dye demonstrations and interpret the results together with UF/IFAS recommendations [28]
Florida drip irrigation school	A UF/IFAS one-day-long educational program with hands-on demonstrations of drip irrigation installation, maintenance and operation, nutrient movement in the soil and correct calculation of nutrient injection rates
Face-to-face food safety training	How to develop a farm and packing house food safety manual and prepare and respond to a food safety audit as required by the buyer
Phone apps	From irrigation suppliers (HydraWise, Crop Water, Irrigate Cost, Irrigate Pump [z]) From universities (Cotton Irrigation App; Urban Turf App [29])

[z] For information only; not recommended by the University of Florida.

The most common mistakes made by vegetable growers may be categorized as: (1) improper soil sampling; (2) incorrect calculations; (3) unnecessarily high preplant fertilizer rates; (4) relying solely on observation (or "guessing") to determine crop nutrient and water needs; and (5) believing that "more" nutrients and "more" water are good for the crop. Historically, organic growers have taken the approach to add fertilizer or compost at the beginning of the season at a rate that will provide the most N possible without risk of burning the crop, but this practice is not ideal. High preplant rates of organic fertilizers (compost or manures) in warm, sandy soils are much more vulnerable to mineralization and leach N faster than in cooler conditions [22].

On-farm demonstrations are one way Extension agents can help vegetable growers improve their practices. For example, on-farm trials have been regularly conducted in North Florida by Extension faculty for the last 30 years. By monitoring crop nutrient status with ion-specific electrodes, by measuring soil moisture content with hand-held Time Domain Reflectometry probes, and by injecting dye that shows where the water moves in their mulched beds, growers have learned that limiting the application of fertilizer in the bed row rather than broadcast over the entire field reduces the risk of nutrient leaching and reduces fertilizer expense. They also learned that soluble nutrients such as N and K move in the soil solution downward through the soil profile with excessive irrigation [18]. Consequently, they have reduced their irrigation rates rather than increasing fertilizer rates in order to avoid nutrient deficiencies. They also learned that application rates of organic-compliant fertilizers must take into account anticipated mineralization rates based on temperature and moisture which are controlled by cultural practices and environmental conditions.

Extension classes and demonstrations have resulted in broad changes by the vegetable industry in North Florida, especially by watermelon growers. Watermelon growers have reduced the N rate applied prior to bedding and mulching from 100–150 kg/ha down to 25–50 kg/ha since the beginning of these programs 20 years ago. The remaining N is now calculated and applied correctly through the drip system over the season. Therefore, a total reduction of 75 to 100 kg/ha of N per year has resulted directly from these demonstrations without affecting watermelon yield or quality. The final resulting N and water management programs on these farms are accepted Best Management Practices for growing watermelons using plasticulture [12].

In organic systems, nutrient management decisions (selection of sources and timing of application) are further complicated by the food-safety mandates of the U.S. Food Safety Modernization Act of 2011 (PL 111-353). Nutrient sources that include animal wastes are of particular concern. Farmers have to consider if the animal waste sources are composted using standardized composting procedures, or if they are untreated animal wastes. If untreated animal wastes are used, food safety audits typically require the untreated animal wastes to be applied to the crop more than 90–120 days before harvest, depending on the crop growth habit. Those crops grown with the harvested portion in or near the ground generally require a longer period (120 days) between application and harvest.

However, in some U.S. markets, very strict guidelines may completely prohibit the use of any animal wastes even in organic production, thus drastically limiting the fertilization options. Fruit and vegetable farmers in the U.S. today have to understand the much greater complexities of regulations for both water and nutrient management, and for food safety. Often food safety regulations impose longer periods required between animal waste applications and harvest, resulting in all fertilizer applied preplant. This practice increases the risk of nutrient leaching and directly contradicts the expectations of the Best Management Practice plans.

7. Effects of Insufficient Water or Nutrients on Vegetable Postharvest

Vegetable water contents are typically above 85%, which illustrates the importance of water supply during vegetable crop production. When the water supply is limited, critical periods of crop water needs and crop drought tolerance indices have been proposed to best use the available water [30]. These periods usually correspond to the development of the harvested plant part. However, as fast-growing plants, vegetable crops need a continuous adequate supply of water and nutrients.

When soil water tension remains above 25 kPa for several hours, plant growth and yields are reduced [31].

All essential elements contribute to maximizing the postharvest potential of vegetables. Specific nutrient imbalances associated with postharvest disorders include softening caused by excess N (grey wall of tomato (*Solanum lycopersicon* L.) or hollow stem of broccoli (*Brassica oleracea var.* italica), for example) and blossom-end-rot caused by an insufficient Ca supply [32,33].

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