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Comparison of 14 Methods to Determine Heat Unit Requirements for Cucumber Harvest

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Abstract. **Fourteen methods of calculating heat units from planting to harvest were applied to daily maximum and minimum air temperatures taken in a standard weather shelter for 2 growing seasons (spring and summer) over 5 years of cucumber (*Cucumis sativus* L.) plantings in North Carolina. The coefficient of variation (CV) was used to determine which of the methods was most reliable in predicting day of first harvest. The best method was to sum over days from planting to harvest the difference between the daily maximum and a base temperature of 15.5°C; but if the maximum exceeded 32°, it was replaced by 32° minus the difference between the maximum and 32°, before subtracting the base. This method had a CV of 3%, compared with 10% for the standard method—numbers of days from planting to harvest.**

Techniques for summing heat units have widespread application for predicting stages of development for many crops (18). Using peas (*Pisum sativum* L.), Boswell (3) was the first to apply the concept of heat summations relative to vegetable crop production. He found that blossoming occurred after the peas received a particular amount of heat above 4°C, regardless of the number of days involved. Research with sweet corn (*Zea mays* L.) showed that cultivars adapted to the southern United States required more heat units to mature than those adapted to the northern United States (12). Arnold (1) demonstrated that the appropriate base temperature can be calculated using heat unit summations from a series of plantings by choosing the base temperature giving the smallest coefficient of variation (CV). He showed that the CV method was correlated closely with the method proposed by Hoover (6), which used regression of daily mean temperature on heat unit accumulations for different environments.

A modification wherein the heat unit totals were multiplied by daylength has been used for lettuce (*Lactuca sativa* L.) (11) and for peas (14). This procedure also was used to compensate for differences in growth over different seasons for snap beans (*Phaseolus vulgaris* L.) (5). An additional modification was used by Madariaga and Knott (11) to control variability caused when temperatures exceeded a maximum for plant growth. They introduced the idea of a temperature ceiling, considering daily maxima that exceeded 21°C as being 21° before summing the heat units. Gilmore and Rogers (4) also subtracted the number of degrees by which the daily maximum exceeded the ceiling from the daily mean temperature.

Katz (8) suggested that an error was introduced by using temperatures collected from weather stations that were in different microclimates from the field where the crop was planted and that weather data collected at crop height was needed.

Baskersville and Emin (2) described a heat accumulation method based on the assumption that the diurnal temperature curve is similar to the trigonometric sine curve. Logan and Boylan (10) further refined this model for tomato (*Lycopersicon esculentum* Mill.) by adding 3 constraints: a) a minimum temperature below which plant growth stops; b) a high temperature above which plant growth remains unchanged; and c) a maximum high temperature above which plant growth is retarded. They concluded that the sine function model should perform more consistently than the traditional heat unit model.

Parton and Logan (13) modeled the diurnal variation in soil and air temperature given the daily maximum and minimum. They used a truncated sine wave to predict daytime temperatures and an exponential function to predict nighttime temperatures. Wann et al. (17) evaluated the model of Parton and Logan (13) relative to the sinusoidal model (19) and a variation of the sinusoidal model (7) that uses a truncated sine function of one-quarter period instead of a half period cosine function for the interval between the times of the minimum and maximum temperatures. Wann et al. (17) found that the sine–exponential model of Parton and Logan (13) improves the fit to observed data and is superior for calculating diurnal variation in air temperature from daily maximum and minimum temperatures.

A more reliable prediction of harvest maturity than the standard method of counting days from planting to harvest (which varies over types and maturity groups from less than 35 to more than 63 days in North Carolina) is needed. The objective of this research was to apply methods of heat-unit summation to harvest date for fresh-market and pickling cucumbers (*Cucumis sativus* L.).

The data for this comparative study were taken from 2 growing seasons (spring and summer) over 5 years (1980–1984). Two or 3 maturity groups, determined from the percentage of fruit weight in the first 2 of 6 harvests (0–19% is late, 20–29% is midseason, and 30–100% is early) of 2 crops (early, midseason, and late fresh-market cucumbers and early midseason pickling cucumbers), were grown at the Horticultural Crops Research Station near Clinton, N.C. (Table 1). Cultivars were grouped by maturity, based on 10 years of yield trial data taken in North Carolina. Maturity was classified using percentage of total yield in the first week of harvest. Daily maximum and minimum air temperatures were recorded from a mercury-in-glass thermometer in a standard National Weather Service shelter.

Plots were hand-seeded on raised beds in single rows spaced 1.5 m apart (center to center) and were 6 m long. Plots were thinned to about 50,000 plants/ha for fresh-market cucumbers and 70,000 plants/ha for pickling cucumbers. Depending on the year, the spring crop was seeded between 19 Apr. and 2 May, and the summer crop was seeded between 6 and 12 July (Table 2). The first harvest was made when fruits were marketable, but before they became oversized (>60 mm diameter for fresh-market cucumbers and >51 mm diameter for pickling cucumbers). Standard cultural practices were used for all crops. The soil was treated during the October before planting with the nematicide, dichloropropene (1,2-dichloropane 1,3-dichloropropene) at 93 liter per ha. Prior to bed formation in the spring, 90N–20P–74K (kg/ha) was broadcast. At that time, tank-mixed bensulide (0,0-bis(1-methylethyl)S-[2-[(phenylsulfonyl)amino]ethyl]phosphorodithioate) and naptalam (2-[(1-naphthalenylamino) carbonyl]benzoic acid) were incorporated at rates of 9.9 and 4.5 kg/ha, respectively. Postplant fertilizer consisted of a sidedress application of 34 kg N/ha. Irrigation was applied using

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Table 1. The 37 and 32 cultivars (of pickling and fresh-market cucumbers, respectively) used to develop the heat unit requirement (°C-days) from planting to first harvest.

Cultivar type	Maturity group[z]		
	Early	Midseason	Late
Fresh-market	Lama	Dasher	Ashley
	Raider	Dasher II	Comanche 7
	Revenue	Castlemaster	Early Triumph
	Slice King	Centurion	Marketmore 72
	Slice Nice	Cherokee 7	Marketmore 76
	Slicemaster	Coolgreen	Marketmore 80
	Sprint 440 S	Guardian	Marketsett
	Sprint 440 II	Jet Set	Pacer
	Superset	Medalist	Poinmarket
		Slice More	Poinsett 76
		Verino	Slice
			Super Slice
Pickling	Blitz	Clinton	
	Calico	Pennant	
	Calypso	Saladin	
	Carolina	SMR 58	
	Cascade	Sumter	
	Castlepik	Triple Pak	
	Chemset		
	Commander		
	Earlipik 14		
	Explorer		
	Fremont		
	Greenpak		
	Gynomite		
	Lucky Strike		
	Medusa		
	Multipik		
	Panorama		
	Pikmaster		
	Pinnacle		
	Regal		
	Reliance		
	Salvo		
	Sampson		
	Score		
	Southern Belle		
	Tamor		
	Target		
	Tempo		
	Totem		
	Triple Crownf		
	Triplemech		

[z]Determined from the percentage of fruit weight in the first 2 of 6 harvest (0–19% is late, 20–29% is midseason, and 30–100% is early). No pickling cultivars were late maturing.

Table 2. Planting and harvest dates for early, mid-, and late season fresh-market and pickling cucumbers for 5 years and 2 seasons.

Cucumber type	Year	Season	Planting date	Harvest dates for cultivars of 2 or 3 different maturities		
				Early	Mid	Late
Fresh-market	1980	Spring	1 May	23 June	26 June	30 June
	1981	Spring	27 Apr.	18 June	22 June	5 June
	1982	Spring	19 Apr.	14 June	17 June	21 June
	1983	Spring	2 May	23 June	27 June	30 June
		Summer	11 July	25 Aug.	29 Aug.	2 Sept.
	1984	Spring	30 Apr.	18 June	21 June	25 June
		Summer	6 July	16 Aug.	20 Aug.	23 Aug.
Pickling	1980	Spring	1 May	16 June	19 June	---[z]
		Summer	10 July	18 Aug.	21 Aug.	---
	1981	Spring	27 Apr.	15 June	18 June	---
		Summer	7 July	18 Aug.	21 Aug.	---
	1982	Spring	19 Apr.	7 June	10 June	---
		Summer	12 July	16 Aug.	19 Aug.	---
	1983	Spring	2 May	20 June	23 June	---
		Summer	11 July	22 Aug.	25 Aug.	---
	1984	Spring	30 Apr.	14 June	18 June	---
		Summer	6 July	13 Aug.	16 Aug.	---

[z]No late-maturing pickling cucumber cultivars.

overhead sprinklers as needed to supplement natural rainfall and to provide about 25 to 38 mm of water to the field each week. Not all cultivars were tested in all seasons and years, ranging from 9 to 19 of the pickling lines and 11 to 18 of the fresh-market types in the seasons and years sampled.

Number of days from planting through first harvest was used as the standard of comparison for summations of heat units. Heat unit summations were determined by 14 methods, using 5 base values (0°, 10°, 13°, 15.5°, and 18°C) and different ceiling temperatures. Base temperatures were selected to be a range around the base of 13° for cucumbers (15).

Method 1. Standard growing degree day (GDD) computation:

$$GDD = \Sigma\ (\text{Mean - Base}), \quad [1]$$

where mean = (daily maximum + daily minimum air temperature)/2.

Method 2. Use daily maximum instead of mean air temperature:

$$GDD = \Sigma\ (\text{Maximum - Base}) \quad [2]$$

Method 3. If maximum is greater than the given ceiling (ceiling = 27°, 29°, 32°, or 35°C), then set maximum equal to ceiling and use Eq. [1]. Ceiling values were based on example optimum temperatures presented by Arnold (1).

Method 4. Same as Method 3, but use Eq. [2].

Method 5. If maximum is greater than the given ceiling (same values as in Method 3), set maximum equal to the ceiling minus the difference between the maximum and ceiling, then use Eq. [1].

Method 6. If maximum is greater than the given ceiling (same values as in Method 3), set maximum equal to the ceiling minus the difference between the maximum and ceiling, then use Eq. [2].

Method 7. If maximum is greater than the given ceiling (same values as in Method 3), subtract the difference between the maximum and ceiling from the daily mean, then use Eq. [1].

Method 8. Sum growing degree hours (GDH) by using Eq. [1] for each hourly mean. The hourly means used in this method were derived from a slightly modified version of the sine–exponential model of Parton and Logan (13) developed by Linvill (9). This model requires a 3rd parameter (daylength) in addition to maximum and minimum temperatures. Four steps were used in developing the equation for daylength.

A formula for daylength (DL) at any given latitude and day of the year was derived as follows. The solar declination angle is first computed from the relationship:

$$\tan \delta = \tan (23.45°) \sin (X), \quad [3]$$

where δ is the solar declination angle (angular distance of sun north of the equator) and X is the right ascension of the sun, being 0° at the vernal equinox, 90° at the June solstice, and so on. Thus, X changes about 360/365.25, or 0.9856 degrees per day. On 21 March, $\tan \delta = 0$ and $\delta = 0$. A value for

Table 3. Coefficients of variation (CV) for 14 methods of calculating heat unit summations with varying base and ceiling temperatures vs. days from planting to harvest.

	Temperature (°C)				Temperature (°C)				Temperature (°C)		
Method	Base	Ceiling	CV	Method	Base	Ceiling	CV	Method	Base	Ceiling	CV
1	0	None	6	4	0	32	7	6	0	32	8
	10	None	11		10	32	4		10	32	4
	13	None	15		13	32	5		13	32	4
	15.5	None	22		15.5	32	6		15.5	32	3
	18	None	32		18	32	8		18	32	3
2	0	None	6	4	0	35	6	6	0	35	6
	10	None	7		10	35	6		10	35	5
	13	None	8		13	35	7		13	35	6
	15.5	None	10		15.5	35	9		15.5	35	7
	18	None	14		18	35	12		18	35	10
3	0	27	7	5	0	27	8	7	0	27	8
	10	27	7		10	27	6		10	27	6
	13	27	10		13	27	7		13	27	7
	15.5	27	16		15.5	27	11		15.5	27	11
	18	27	27		18	27	22		18	27	22
3	0	29	6	5	0	29	7	7	0	29	7
	10	29	8		10	29	5		10	29	5
	13	29	11		13	29	7		13	29	7
	15.5	29	16		15.5	29	11		15.5	29	11
	18	29	25		18	29	18		18	29	18
3	0	32	6	5	0	32	6	7	0	32	6
	10	32	9		10	32	7		10	32	7
	13	32	13		13	32	11		13	32	11
	15.5	32	19		15.5	32	16		15.5	32	16
	18	32	28		18	32	24		18	32	24
3	0	35	6	5	0	35	6	7	0	35	6
	10	35	11		10	35	10		10	35	10
	13	35	15		13	35	14		13	35	14
	15.5	35	21		15.5	35	20		15.5	35	20
	18	35	31		18	35	29		18	35	29
4	0	27	9	6	0	27	13	8	15.5	None	20
	10	27	7		10	27	20	9	15.5	32	19
	13	27	7		13	27	23	10	15.5	32	17
	15.5	27	6		15.5	27	29	11	15.5	None	14
	18	27	5		18	27	39	12	15.5	32	12
4	9	29	8	6	0	29	10	13	15.5	32	10
	10	29	5		10	29	11	14	15.5	32	3
	13	29	5		13	29	11		Days (planting) to harvest)		
	15.5	29	4		15.5	29	12				10
	18	29	5		18	29	14				

δ for each day of the year after 21 March can thus be computed from:

$$\tan \delta = \tan (23.45°) \sin [(0.9856) (J)] \quad [4]$$

where J is the day number after 21 Mar. The value of tan δ in Eq. [4] is substituted in the formula from Sellers (16):

$$\cos H = -\tan \phi \tan \delta, \quad [5]$$

to derive a value for the half daylength H, where φ is latitude. Thus,

$$H = \cos^{-1} (-\tan \phi \tan (23.45°) \sin [(0.9856) (J)) \quad [6]$$

or

$$DL = 2H = 2 \cos^{-1} (-\tan \phi \tan (23.45°) \sin [(0.9856) (J)]. \quad [7]$$

Dividing DL by 180° and then multiplying by 12 gives the value for daylength in hours.

Method 9. Same as Method 8, but reset maximum as in Method 3.

Method 10. Same as Method 8, but reset maximum as in Method 5.

Method 11. Sum GDH accumulated during daytime only.

Method 12. Same as Method 11, but reset maximum as in Method 3.

Method 13. Same as Method 11, but reset maximum as in Method 5.

Method 14. Same as Method 1, but multiply by daylength.

Methods 2, 4, 5, and 6, which used only the daily maximum, and Methods 8–13, which used hourly temperature data, were originated by the authors. The CV was used as recommended by Arnold (1) to identify the best method for predicting first harvest. CVs were calculated for each maturity group of each crop type over the 2 seasons and the 5 years. Thus, heat units (or days) from planting to harvest were used to calculate a CV for each maturity group of each crop type. Data were the mean values for each season of each year (7–10 data points for each CV). Mean CVs were calculated using the values averaged over the 5 maturity group–crop type combinations. The mean CV over the 2 seasons and the 5 years for each heat unit summation method was used to identify the one with the least variation over test environments.

Comparison of the CVs calculated for each method showed that Methods 6 and 14 had the least variation in the interval from planting to first harvest (Table 3). Method 14 used daylength as a weighting factor for each day's heat unit accumulation. Because methods 6 and 14 had the same CV, 3% for the 15.5°/32°C and 18°/32° (base/ceiling) combination, but Method 14 required additional information, it was decided to evaluate Method 6 further.

The base of 15.5°C and a ceiling of 32° were selected over the base of 18° and ceiling of 32°, based on Arnold's (1) observation that an underestimate of the base reduces error in predicted days to harvest. Therefore, it was decided to test 0.5° intervals around that combination to determine whether the CV could be reduced further. All possible 0.5° combinations of the base temperatures (14.5°, 15°, 15.5°, 16°, and 16.5°) and the ceiling temperatures (31°; 31.5°, 32°, 32.5° and 33°) were evaluated. However, none of the new combinations was an improvement over the 15.5°/32° combination, with CVs

Table 4. Coefficients of variation for 2 crop types and 2 or 3 maturity groups using Method 6 for combinations of base and ceiling temperatures at small intervals around base = 15.5°C and ceiling = 32°.

Temperature (°C)		Coefficient of variation					
		Pickling		Fresh-market			
Ceiling	Base	Early	Mid	Early	Mid	Late	Mean[z]
31	14.5	6	5	6	6	5	6
	15	6	5	6	6	5	6
	15.5	6	5	6	5	5	5
	16	6	5	6	5	5	5
	16.5	5	5	6	5	5	5
31.5	14.5	5	4	4	4	4	4
	15	5	4	4	4	4	4
	15.5	5	4	4	4	3	4
	16	4	4	4	3	3	4
	16.5	4	3	4	3	3	4
32	14.5	4	4	3	2	2	3
	15	4	4	2	2	2	3
	15.5	4	4	2	2	2	3
	16	4	4	2	2	2	3
	16.5	4	4	2	2	2	3
32.5	14.5	5	4	2	2	2	3
	15	5	4	2	2	2	3
	15.5	5	4	2	2	2	3
	16	5	5	2	2	2	3
	16.5	5	5	2	3	3	4
33	14.5	6	5	2	2	3	4
	15	6	5	2	3	3	4
	15.5	6	6	3	3	3	4
	16	7	6	3	3	4	5
	16.5	7	6	3	4	4	5

[z]Mean overall maturity groups of pickling and fresh-market cucumbers.

ranging from 3% to 6% on the average (Table 4). The cvs for each of the 5 crop type–maturity group combinations increased as the base, and especially the ceiling, temperatures were raised or lowered from the 32°/15.5° combination, even for a 0.5° interval. Thus, the best method for predicting harvest date was Method 6 with a base of 15.5° and a ceiling of 32°.

Although the trend is away from once-over mechanical harvest for pickling cucumbers at present, once-over harvesting probably will become increasingly important in the future. Once-over harvesting and fewer hand harvests per crop season make prediction of the date of first harvest more important. The date of first harvest might be predicted by using climate data for a particular production region. By using Method 6 and knowing the number of heat units required to reach first harvest for a crop type and maturity group (Table 5), a grower could schedule plantings so that one would be finished harvesting as a 2nd was beginning harvest. This prediction technique provides a management tool by which a grower could improve schedules of preharvest cultural practices, labor, and machinery.

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Table 5. Days from planting to harvest and heat unit summation for Method 6 for early, midseason, and late fresh-market and pickling cucumbers for 5 years and 2 seasons.

			Maturity class					
			Early		Mid-season		Late	
Cucumber type	Year	Season	Days	Heat units (°C days)	Days	Heat units (°C days)	Days	Heat units (°C days)
Fresh-market	1980	Spring	53	662	56	697	60	753
	1981	Spring	52	634	56	696	59	742
	1982	Spring	56	643	59	684	63	736
	1983	Spring	52	657	56	719	59	768
		Summer	45	638	49	697	53	756
	1984	Spring	49	632	52	672	48	727
		Summer	41	622	45	682	48	721
	$\overline{X}$		50	641	53	692	56	743
Pickling	1980	Spring	46	582	49	609	---[z]	---
		Summer	39	580	42	626	---	---
	1981	Spring	49	597	52	634	---	---
		Summer	42	625	45	649	---	---
	1982	Spring	49	558	52	597	---	---
		Summer	35	539	38	584	---	---
	1983	Spring	49	614	52	657	---	---
		Summer	42	602	45	638	---	---
	1984	Spring	45	575	49	632	---	---
		Summer	38	574	41	622	---	---
	$\overline{X}$		43	585	47	625	---	---

[z]No late-maturing pickling cucumber cultivars.

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Growth and Nutritional Status of Petunia and Tomato Seedlings with Acidified Irrigation Water

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Abstract. **Seed of *Lycopersicon esculentum* Mill. 'Champion' and *Petunia hybrida* Vilm. 'Snow Cloud' were irrigated with either nonacidified solution (0.15, 0.30, or 0.45 ml) of 75% $H_3PO_4 \cdot liter^{-1}$; or 0.11, 0.20, or 0.26 ml of 46.5% $H_2SO_4 \cdot liter^{-1}$. Germination was not affected by acidification, yet seedling growth was enhanced for both species. Growing medium and plant shoots were analyzed for N, P, K, Ca, and Mg content. Although nutrient levels were affected by acidification, no nutrient deficiency or phytotoxicity due to irrigation water acidification was evident.**

Water pH can be a limiting factor in greenhouse crop production. Nutrient availability and subsequent plant growth can be affected severely by high medium and irrigation water pH (1, 5, 6, 8, 12, 13). The recommended range of irrigation water pH for greenhouse crops is 5.0 to 6.5 (5, 6, 13).

Phosphoric or sulfuric acid generally is used to reduce high water pH (2, 5, 6). However, use of phosphoric acid may cause phosphorus build up to undesirable levels in plug-production media (9).

This experiment was designed to study the influence of irrigation water acidification in plug production on: a) seed germination and subsequent seedling growth; b) plant nutrient status and soil fertility levels; and c) the effects of relatively high rates of phosphoric or sulfuric acid as water-acidifying agents.

Species grown were tomato ('Champion') and petunia ('Snow Cloud'). Treatments were replicated 4 times, with each replication consisting of 50 seeds sown in 2.2 × 4.5 cm (diameter × depth) plug trays. A completely random design was used for placement on the bench. Jiffy Mix was used as planting medium (Table 1). Seeds were sown 14 Feb. 1985 and irrigated with tap water; 0.15, 0.30, or 0.45 ml of 75% $H_3PO_4 \cdot liter^{-1}$ of tap water; or 0.11, 0.20, or 0.26 ml of 46.5% $H_2SO_4 \cdot liter^{-1}$ of tap water. Irrigation solutions were amended with 0.667 g of 15N-7P-14K$\cdot liter^{-1}$ starting 1 Mar. 1985, supplying 100 ppm N, 47 ppm P, and 94 ppm K as a constant feed. Solution pHs and electrical conductivities were recorded every other irrigation (Table 2). Seedlings were grown in a glass greenhouse using natural photoperiods. Day and night temperatures were 24°C and 22°, respectively. Plug trays were covered with translucent polyethylene until seedling emergence was evident. Each replicate (tray) was subirrigated independently by placement on a capillary tray filled with solution. The numbers of germinated seedlings were recorded 24 Feb. 1985. Ten tomato and petunia plants per replication were harvested 18 Mar. and 28 Mar. 1985, respectively. Data collected at harvest included dry weight and leaf number per plant for both species and length and width of the first compound leaf for tomatoes. At harvest, the growing medium for all plug cells of each tray (replication) was combined and a 300-ml sample of medium from each tray was used for nutrient analysis. Saturated paste extract of growing medium was obtained by suction filtration through a single layer of Whatman No. 1 filter paper. Extract was analyzed for pH using a Fisher Accumet model 810 glass electrode pH meter. Nitrate-N concentration was measured with an Orion Nitrate Electrode Model 92-07 using an Orion Ionanalyzer Specific Ion Meter, Model 401. Ammonia-N levels were determined by Nesslerization, and P was determined by an ammonium molybdate–amino napthol sulfonic acid reduction procedure, using a Bausch and Lomb Spectronic-20. Concentration of K, Ca, and Mg were determined with a Unicam SP 90 AA spectrophotometer. Plant tissue was dryed in a forced-air dryer heated to 65° for 72 hr, then ground through a 20-mesh screen in a Wiley Mill. One 100-mg tissue sample of each replication was digested with 2.2 ml H_2O_2 and 1 ml $HClO_4$. Concentrations of N, P, K, Ca, and Mg in shoots were determined as described previously. Data were subjected to analysis of variance, and single degree of freedom tests were used for contrasts between treatments.

Tomato. Tomato germination was not affected by any treatment and averaged 90% ± 4%. All growth parameters measured were significantly greater for acid treatments than for controls (Table 3). Thus, acidification of alkaline irrigation solution appears beneficial to tomato seedling growth. No statistical difference between acids was observed for any growth parameters measured (H_3PO_4 vs. H_2SO_4 single degree of freedom test). Plant dry weight, stem length, and the length of the first compound leaf exhibited a quadratic response to phosphoric acid concentration, with 0.3 ml $H_3PO_4 \cdot liter^{-1}$ showing the greatest growth (Table 3). Number of leaves per seedling and the width of the first com-

Table 1. Nutrient levels of unplanted Jiffy Mix growing medium using saturated paste extract method of analysis.

Parameter	Measured level
pH	6.7
Electrical conductivity	2.6 $dS \cdot m^{-1}$
NO_3-N	195 ppm
NH_4-N	1 ppm
P	30 ppm
K	208 ppm
Ca	88 ppm
Mg	82 ppm

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