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PLANT FEATURES MEASUREMENTS FOR ROBOTICS

PREPARED BY:	Dr. Gaines E. Miles
ACADEMIC RANK:	Professor
UNIVERSITY AND DEPARTMENT:	Purdue University Department of Agricultural Engineering
NASA/KSC	
DIVISION:	Biomedical Operations and Research
BRANCH:	Life Sciences Research Office
NASA COLLEAGUE:	Mr. Ralph P. Prince
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Abstract

Initial studies of the technical feasibility of using machine vision and color image processing to measure plant health were performed. Wheat plants were grown in nutrient solutions deficient in nitrogen, potassium, and iron. An additional treatment imposed water stress on wheat plants which received a full complement of nutrients. The results for juvenile (less than 2 weeks old) wheat plants show that imaging technology can be used to detect nutrient deficiencies. The relative amount of green color in a leaf declined with increased water stress. The absolute amount of green was higher for nitrogen deficient leaves compared to the control plants. Relative greenness was lower for iron deficient leaves, but the absolute green values were higher. The data showed patterns across the leaf consistent with visual symptoms. The development of additional color image processing routines to recognize these patterns would improve the performance of this sensor of plant health.

Summary

Wheat plants were grown in solutions deficient in nitrogen, potassium, and iron. Another treatment was to impose a water stress on a plant. Color images of individual leaves were acquired with a machine vision system. Color image processing routines were written to compare the quantified green values and the green trichromatic coefficients for the treatment and control leaves.

Green trichromatic values tended to decline with increased water stress. Green values were higher for nitrogen deficient leaves. Green trichromatic values were lower for potassium deficient leaves, and patterns in the curve matched the location of symptoms. In extreme conditions, iron deficiency resulted in a higher green value and considerably lower green trichromatic values. Patterns in the green curve seemed to match the expected striping pattern. Iron deficiency symptoms developed very quickly and images of classical symptoms were not captured.

This evidence gives rise to expectations that multispectral imaging, combined with additional image processing will be able to clearly detect nutrient deficiencies. A nondestructive means of measuring plant health will lead to the development of a sensor for automatic control of nutrient delivery systems.

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INTRODUCTION

1.1 DESCRIPTION OF THE PROBLEM

Plants grown for food are necessary components of life support systems for long-term space voyages. Current research on a controlled ecological life support system (CELSS) has shown that plants grown in liquid cultures may rapidly develop nutrient deficiencies which affect the performance of a CELSS. If this situation were to occur on a long-term space voyage, it would pose a serious threat to the crew's food supply and life support system.

In terrestrial production systems, low-cost labor is used to visually inspect plants and diagnose disorders. Often the investigation requires tissue analysis which is an invasive, destructive method. In astrocultural production (growth of plants in space) the procedure must be nondestructive and automated to reduce labor and provide the rapid sensing necessary for feedback control of nutrient delivery.

1.2 NUTRIENT DEFICIENCY SYMPTOMS

Much has been written describing the visual symptoms of nutrient deficiencies in plants(1,2,3,4). The following discussion provides an overview and is by no means exhaustive. The lack of sufficient **nitrogen** stunts plant growth, leaves are small and thin. Leaf color is pale-green, yellow-green, or uniformly yellow. Chlorosis (yellowing) is usually more pronounced in older tissue since nitrogen is mobile within plants and tends to move from older to younger tissue when nitrogen is limited. Older leaves first yellow at the tips. In severe cases, tips and margins of older, mature leaves may turn brown (*firing*).

Phosphorus deficiency also stunts plant growth, but leaves turn dark-green, bronzy, reddish-purple, or purplish. Root and grain development is poor and maturity is delayed. Tips of leaves turn brown and die.

Potassium deficiency slows the growth of plants, and results in small fruit or shriveled seeds. Yellowing starts at the tip of older leaves, proceeds along the leaf edge to the base. Finally, tips and margins turn brown (*burn*), starting on mature leaves. Interveinal areas are brown, yellow, or *scorched* in appearance. Stalks are weak and easily lodged. Internodes are shortened.

Iron deficiency results in an interveinal chlorosis of young leaves. Veins remain green, except in severe cases, creating a visibly striped effect along the full length of the leaf. In very severe cases leaves become almost white and growth is stunted.

Leaves of **calcium** deficient plants become hard and stiff, and the margins roll upwards. The growing points and root tips may die. Foliage appearance is abnormally dark-green. Stems become weak, and blossoms and buds shed.

Lack of sufficient **magnesium** stunts plant growth and causes interveinal areas of older leaves to turn yellow. Leaves curl upward along margins. Older leaves show a *chainlike* yellow streaking. Chlorotic areas turn brown and die, starting at the leaf tip.

Sulfur deficiency results in small, spindly plants having a light-green to yellowish-green color in the younger leaves. The top of the plant shows the yellowing first. Affected leaves become thick and firm. Stems are hard, woody, and abnormally elongated and spindly. Symptoms resemble nitrogen deficiency, except there is a more general loss of color.

Manganese deficiency symptoms appear as an interveinal chlorosis of younger leaves. There is a gradual shift from pale green to a darker green next to veins, but there is no sharp distinction between veins and interveinal areas as with iron deficiency. Leaves may become all yellow in severe cases with formation of necrotic spots. Irregular gray specks may develop in oats, interveinal white streaks in wheat, and brown spots and steaks in barley. Plants are stunted with narrow, erect leaves.

Water is perhaps the most important nutrient and symptoms of moisture stress are expressed in many ways. Leaves loose turgidity, wilt, and stomates close. Because transpiration ceases, leaf temperature increases. Stems and leaves usually follow a diurnal pattern of contractions following turgor pressure changes due to transpiration and root uptake.

1.3 PROPOSED SOLUTION

One possible solution to the problem of monitoring plant nutrient status is to use machine vision and image processing to capture images of leaves and extract features which are characteristic of deficiencies. Al-Abbas, Barr, Hall, Crane and Baumgardner (5) showed that the significant differences which exist in the reflectance and transmission properties of maize leaves in the visible spectrum, 400 to 750 nanometers (nm) were due to pigmentation differences (mostly chlorophyll) achieved by nitrogen, potassium, phosphorous, sulfur, calcium, and magnesium deficiencies. Since blue light has a wavelength of approximately 435 nm, green about 546 nm, and red about 700 nm, a solid-state, color video camera should be able to capture these spectral differences as well as the spatial patterns which are characteristic of the various nutrient deficiencies. By interfacing the camera electronically to a computer through a frame-grabber, the array of data from an image can be transferred and stored on disk or memory. Programs can be written to extract and quantisize the salient features and classify the leaf image into one or more deficiency categories.

1.4 OBJECTIVE

The objective of this study is to prove that machine vision and image processing can be used to detect nutrient deficiencies.

PROCEDURES

2.1 PLANT GROWTH

In order to obtain leaves of known, characteristic symptoms, wheat seeds (cv, *Yecora Rojo*) were presoaked, then germinated in a deionized water film. Five days later, a half-strength Hoagland's solution was added. Seven days after initiation, plants were transplanted to aerated, 2 liter jugs filled with a nutrient solution as shown in Table 1. There were 3 replicates of 4 treatments: deficiencies of nitrogen, potassium, and iron; and a normal, or control treatment. Three wheat plants were grown in each jug for a total of 36 plants. Two days after transplanting, all treatments showed visible symptoms characteristic of a deficiency. Each day thereafter, the symptoms became more striking, especially on the new leaf tissues. In the iron and potassium treatments, leaves which formed during germination or during the period when the half-strength Hoagland's solution was available, did not show symptoms to the extent that the newly emerged tissue did. On the other hand, nitrogen deficiency symptoms were observed on new and old tissues.

Lighting was provided by two 400 watt high pressure sodium lamps suspended approximately 75 centimeters (cm) above the plants. The jugs were placed in two rows and covered an area approximately 30 cm x 100 cm.

Water stress was imposed on normal plants by removing them from the nutrient solution. At first the plants were placed in an empty jar, but when excess moisture was observed collecting on the inside walls, the plants were moved into room air at approximately 22 degrees C and 70% relative humidity. Images were taken every 10 minutes during the stress period and the entire process videotaped at 30 frames per second for the 7.5 hour test.

2.2 MACHINE VISION

The apparatus to capture and process the images consisted of a personal computer with a 200 Megabyte disk and tape cartridge for image storage and a color image frame-grabber to simultaneously digitize the red, green and blue signals from a Panasonic CCD color camera (model WV-D5000). A bellows was added to the camera to provide close-up images. Fields of view were on the order of 1 inch or less.

2.3 IMAGE PROCESSING

From each leaf image regions were selected for processing. The first step of processing was to compute the green trichromatic coefficient for each picture element (pixel) according to:

$$G_N = \frac{3G}{R+G+B} * 255 , \qquad [1]$$

where R, G, B refer to the quantified intensity of red, green and blue colors in the image, which are integers varying from 0 to 255. Because leaf width was variable, the pixel data were normalized so that the first element in a column was the bottom edge of the leaf and the 100th element was the top margin. Edges were located with a Sobel operator. This resulted in an image that was independent of field of view (size of leaf) and light intensity. By summing the G_N values across a row and dividing by the number of elements in the row (which varied from one image to the next but was constant within a region), a single curve could be obtained. This gives a visible, quantifiable method of comparing images from each of the treatments.

Because the trichromatic measures the relative amount of a color, the green component was analyzed to provide a quantitative measure of greenness.

From these data two additional features were computed: the average and standard deviation of the green trichromatic coefficients and the green values. The trichromatic average may be considered a single value for *relative greenness* while the standard deviation is a measure of *texture* (6,7,8). These three features: texture, greenness, and curve shape are the basis for detecting nutrient deficiences in plants via machine vision and image processing.

RESULTS AND DISCUSSION

3.1 WATER STRESS

Figure 1 shows the third leaf (newest) of a wheat plant supplied with a control nutrient solution on the 8th day after plants were placed in the jugs. Figure 2 shows the same leaf 7 hours

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* Mention of a manufacturer is for informational purposes only and does not constitute an endorsement of the product to the exclusion of others.

and 40 minutes later in a wilted state. The results of processing the images are shown in Figures 3 and 4. Inconsistency in the Sobel operator's ability to locate the leaf edge may be responsible for the erratic data near the margins. On average the green trichromatic values are higher for the nonstressed or turgid leaf (Table 2), but are not statistically different, possibly due to the difficulty in locating the leaf margin with software. This decline in green with time was consistent for all images taken during the water stress test. One possible explanation is that the loss of turgor also changes the leaf reflectance.

3.2 NITROGEN DEFICIENCY

Figure 5 is an image of the third leaf of a wheat plant after 7 days in a nitrogen deficient solution. A section of this leaf was processed and the results are plotted in Figures 6 and 7. Except at the leaf margins, the green trichromatic values for the control (section A of leaf A1WS1) are higher than the nitrogen-stressed plant. However, the reverse is true for the absolute green values: the nitrogen-stressed values are lower (Table 2). Since a light, or pale-green has a higher absolute value than a dark green, this result was as expected. The control green trichromatic was higher than the nitrogen-stressed plant because the red and blue values changed between the two leaves. On a normal healthy leaf green contributes a higher percentage to the overall reflectance than it does on a nitrogen-stressed leaf.

3.3 POTASSIUM DEFICIENCY

Figure 9 shows a portion of the first leaf of a wheat plant grown in a potassium deficient solution for 4 days. A section was taken and the results are shown in Figures 9 and 10. Although the human eye detects a significant difference in the greenness across the leaf, Figure 9 shows that the actual green values differ very little. On the other hand the green trichromatic values show significant differences. Notice the drop of approximately 100 points in the trichromatic value, beginning with leaf width of 70%. This corresponds to the brown area in Figure 9 which is an obvious symptom of potassium deficiency.

3.4 IRON DEFICIENCY

Figure 11 illustrates the second leaf of a wheat plant grown in iron deficient solution for 9 days. Figures 12 and 13 and Table 2 show the green and green trichromatic values for this leaf. The green values for the iron-stressed plant are higher than the control, but the reverse is true for green trichromatic.

From the earlier description of iron deficiency one would expect the green values to undulate across a leaf, but they do not in Figures 12 and 13. However, on second look at Figure 11, the leaf does not show the usual pattern of iron deficiency. It appears that the second leaf, which had partially formed before the plants were placed in the deficient solution, fails to show a dramatic change in green pattern. Such patterns were observed as early as 2 days, but digitized images were not obtained.

CONCLUSIONS AND RECOMMENDATIONS

This study proves that visual symptoms of some nutrient deficiencies on individual leaves are detectable with machine vision and image processing. Green trichromatic values tend to decline with increased water stress. Green values are higher for nitrogen deficient leaves. Green trichromatic values are lower for potassium deficient leaves, and patterns match the location of symptoms. In extreme conditions iron deficiency results in a higher green value and considerably lower green trichromatic value. Patterns in the green curve seem to match the expected striping pattern. This evidence suggests that other symptoms may be detectable.

Much work remains to develop the technology of machine vision and image processing into a practical sensor for real-time monitoring of plant health. Numerous questions remain concerning positioning the camera and locating a leaf, backlighting, frontlighting, camera resolution, and image processing. Edge detection could be improved by smoothing the edge coordinate data and possibly curve fitting. For potassium deficient detection, an edge-following routine should be developed for both green and red trichromatic values. Using the red curve as a base, deviations in the green and red curves would detect brown spots along the margin of a leaf. Section width is important, but was not studied here. The section must be wide enough to average pixel to pixel differences, but not so wide that significant data (such as brown spots) are averaged into insignificance. A study should be undertaken to determine the section width that provides the greatest information to noise ratio. Another area of study should be to determine the best wavelength(s) to use. Previous research (5) has shown that other nutrient deficiencies can be detected in the near infrared and red spectrums. An optical bandpass filter mounted over the camera lens would enable the same machine vision and image processing to cover at least the near infrared spectrum. These additional studies to prove the capabilities of multispectral video imaging to nondestructively monitor plant health are warranted by the results of this study.

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Figure 1. Photograph of the Wheat Leaf used as a Control (Image A1WS1).

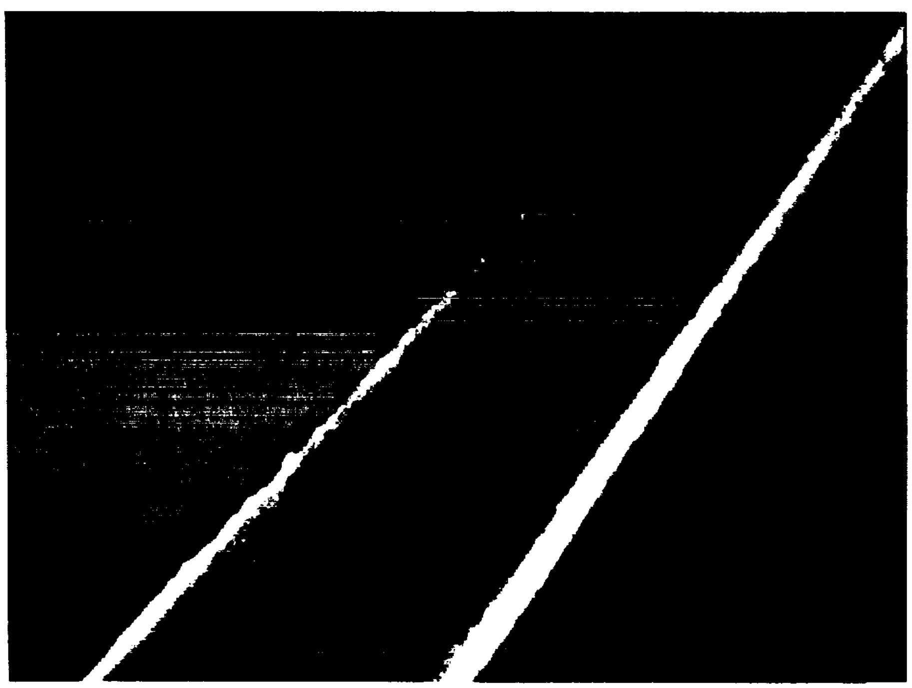

Figure 2. Photograph of a Wilted Wheat Leaf Image A1WS47), 7 Hours and 40 minutes after the Control Image.

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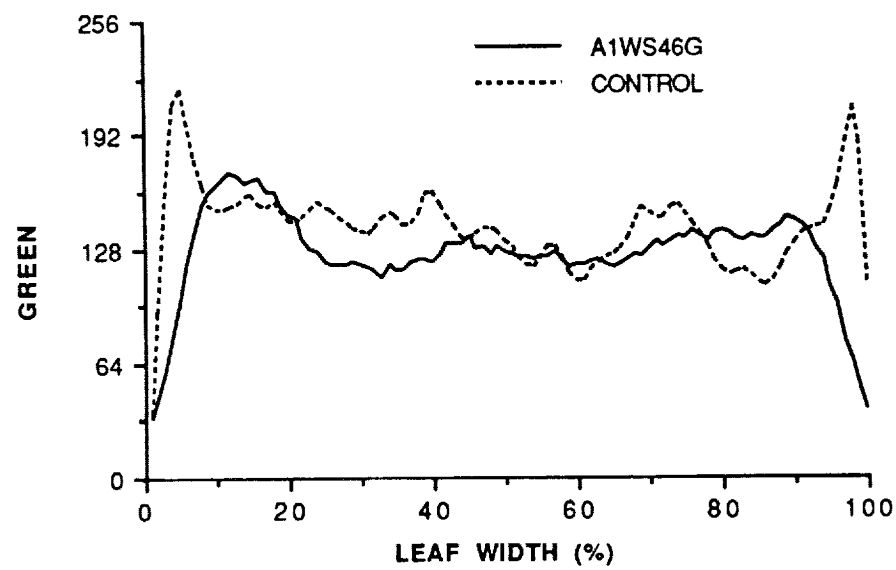

Figure 3. Absolute Measurements of Green for a Turgid (Control, A1WS1A) and Wilted (A1WS46G) Wheat Leaf.

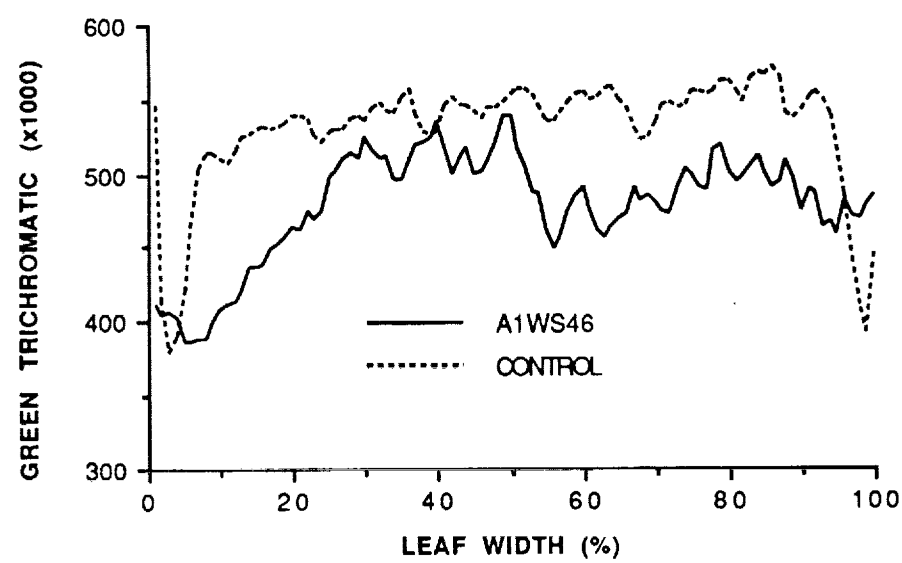

Figure 4. Relative Measurements of Green for a Turgid (Control, A1WS1A) and Wilted (A1WS46G) Wheat Leaf.

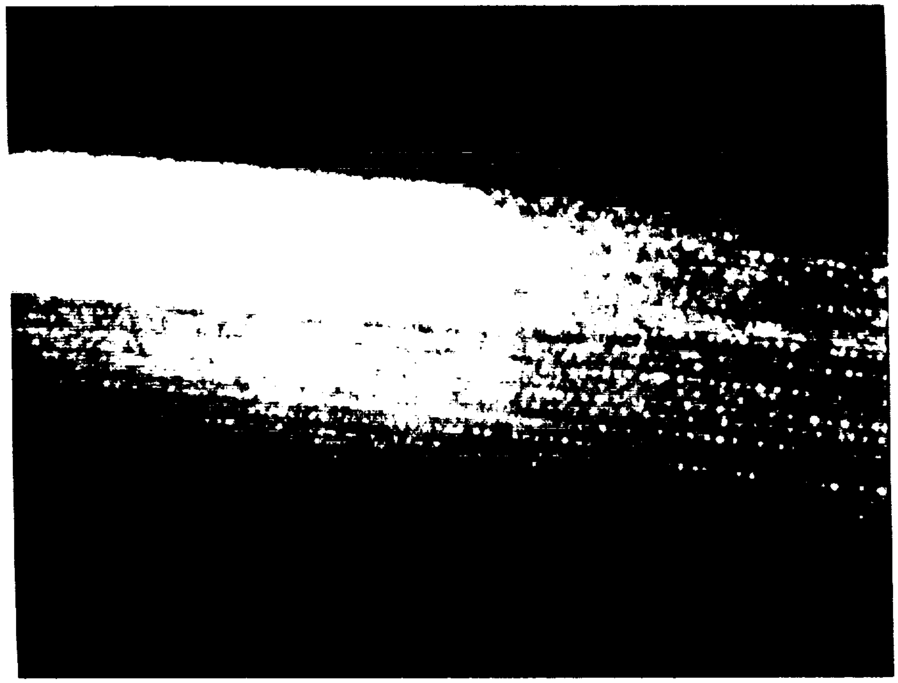

Figure 5. Photograph of a Nitrogen Deficient Wheat Leaf (N112A).

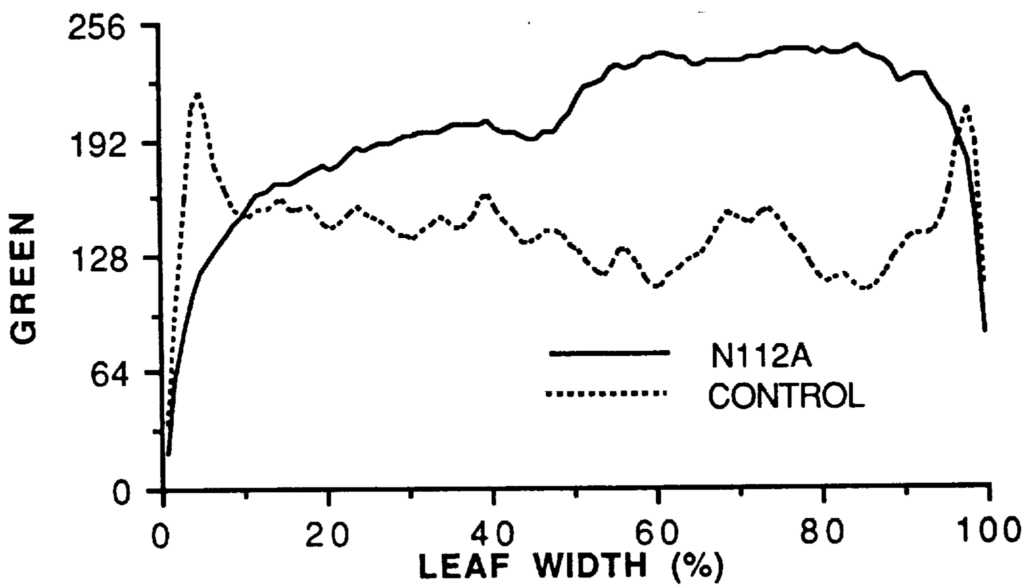

Figure 6. Absolute Measurements of Green for a Nitrogen Deficient Wheat Leaf (N112A).

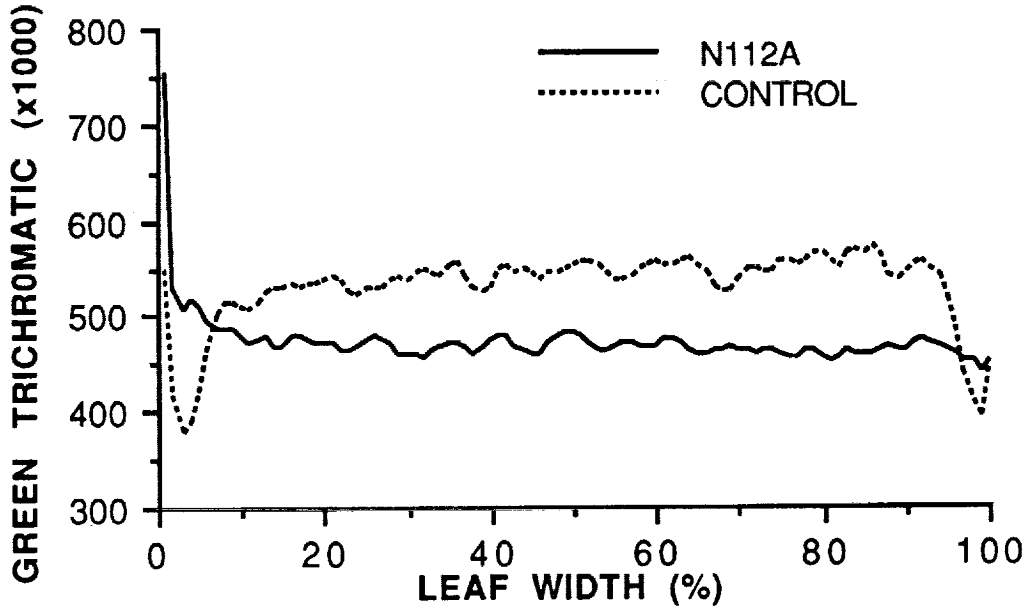

Figure 7. Relative Measurements of Green for a Nitrogen Deficient Wheat Leaf (N112A).

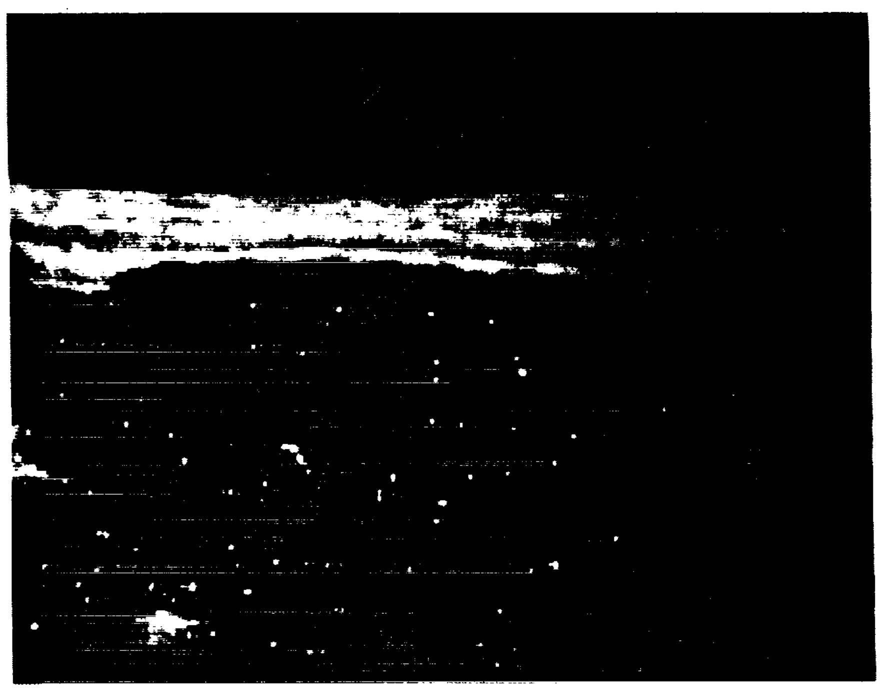

Figure 8. Photograph of a Potassium Deficient Wheat Leaf (K309A).

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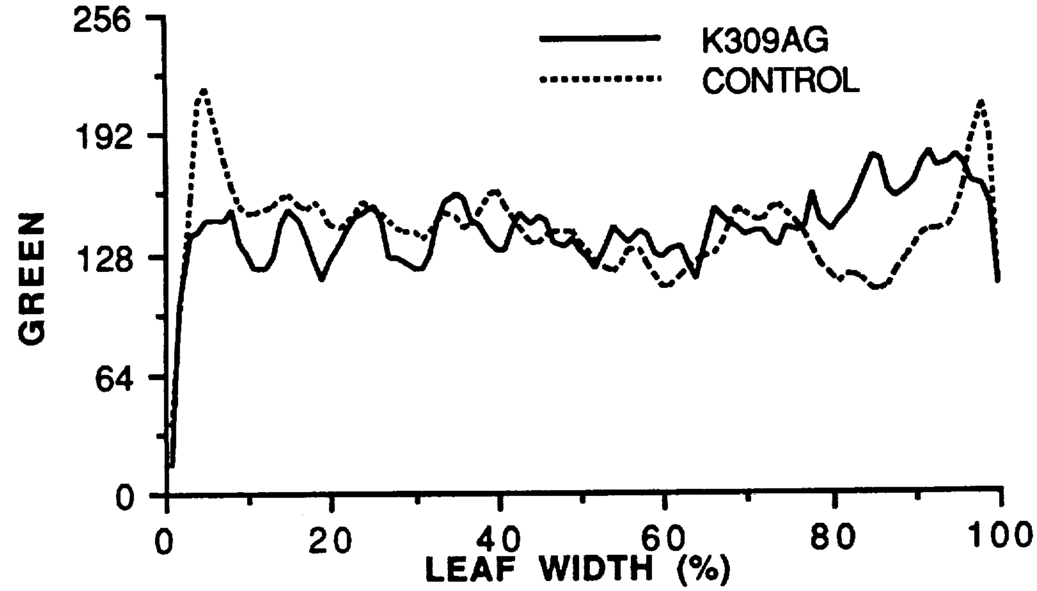

Figure 9. Absolute Measurements of Green for a Potassium Deficient Wheat Leaf (K309A).

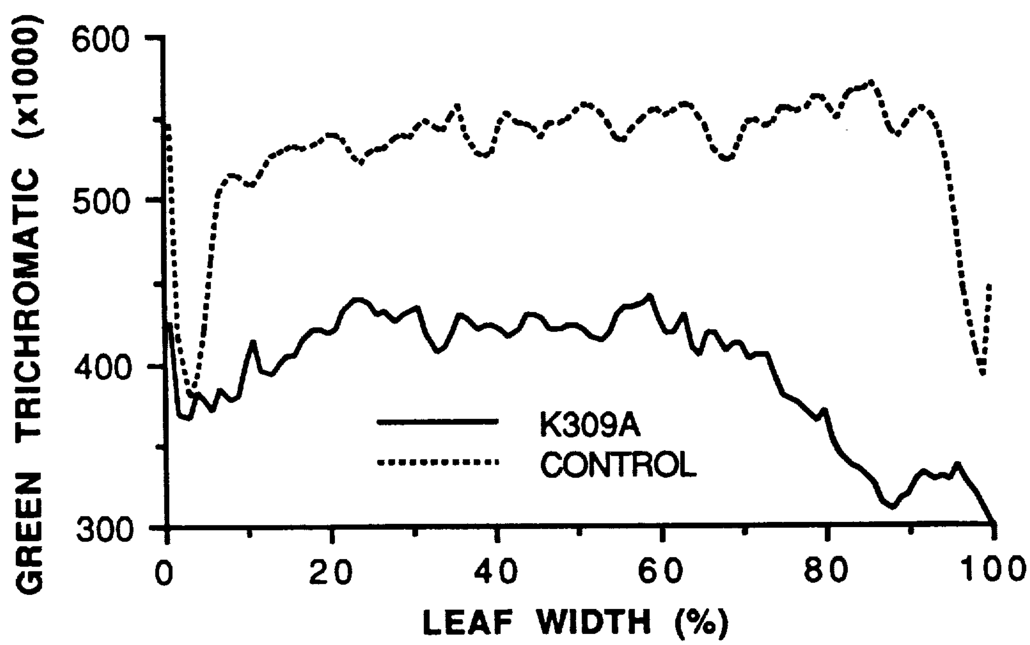

Figure 10. Relative Measurements of Green for a Potassium Deficient Wheat Leaf (K309A).

Figure 11. Photograph of an Iron Deficient Wheat Leaf (F312).

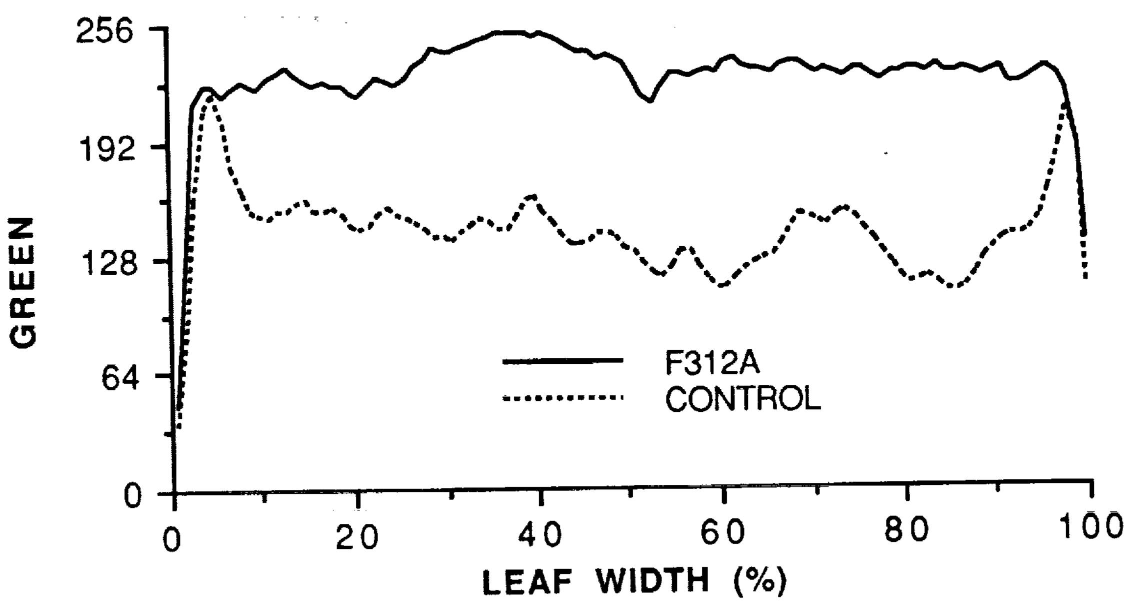

Figure 12. Absolute Measurements of Green for an Iron Deficient Wheat Leaf (F312A).

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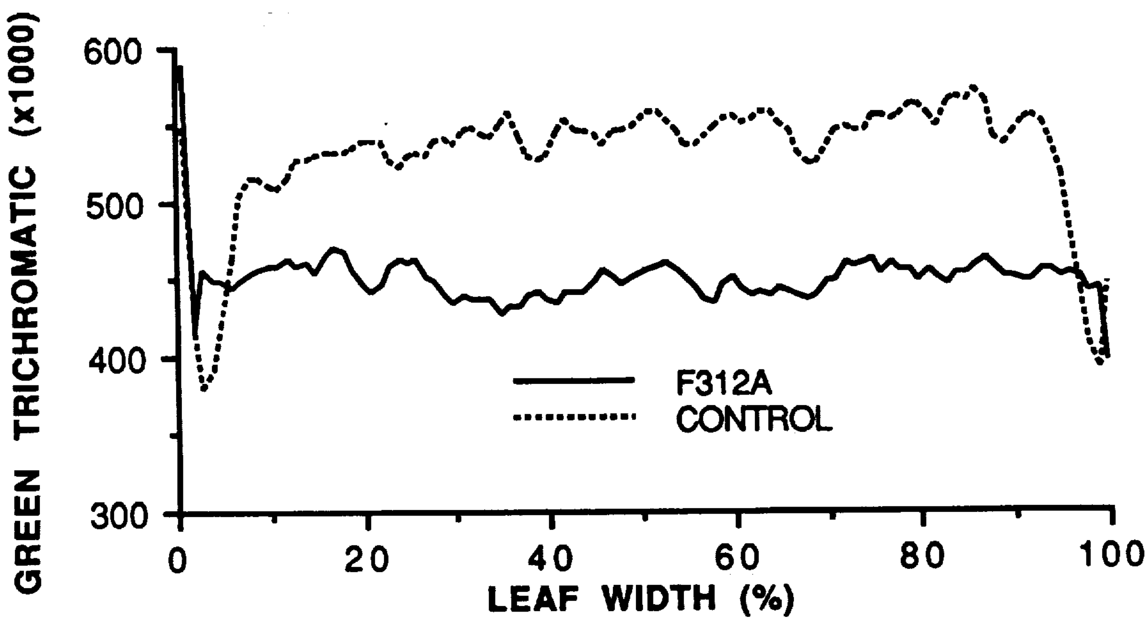

Figure 13. Relative Measurements of Green for an Iron Deficient Wheat Leaf (F312A).

Table 1. Nutrient Solution Formulation

Salt	ADDITIONS Normal (ml/L)	-N (ml/L)	-K (ml/L)	-Fe (ml/L)
$CaCl_2 \cdot 4H_20$		2.50		
K_2SO_4		2.50		
KH_2PO_4	0.50	0.50		0.50
$Ca(NO_3)_2{*}4H_2O$	2.50		2.50	2.50
$(NH_4)_2HPO_4$			0.50	
NH_4NO_3			0.75	
KNO_3	2.50			2.5
$MgSO_4$	1.00	1.00	1.00	1.00
FeEDTA	11.15	11.15	11.15	11.15
micronutrients	1.10	1.10	1.10	1.10

ELEMENTAL CONCENTRATIONS (parts per million)

Element	Normal	-N	-K	-Fe
N	105	0	105	105
P	15.5	15.5	15.5	15.5
K	117	117	0	117
Ca	100	100	100	100
Mg	24	24	24	24
Fe	5.6	5.6	5.6	0
S	32	112	32	32
Zn	0.02	0.02	0.02	0.02
Cu	0.01	0.01	0.01	0.01
Mn	0.20	0.20	0.20	0.20
B	0.21	0.21	0.21	0.21
Mo	0.004	0.004	0.004	0.004

Table 2. Green (G) and Green Trichromatic (GT) Statistics

Treatment	Image	Mean	Std.Dev.
Control	A1WS1AG	140.0	16.2
	A1WS1AGT	530.0	39.5
WATER STRESS	A1WS46G	124.8	25.8
	A1WS46GT	478.2	37.3
IRON DEFICIENCY	F312AG	225.5	24.7
	F312AGT	449.1	17.7
POTASSIUM DEFICIENCY	K309AG	140.0	21.0
	K309AGT	393.5	39.1
NITROGEN DEFICIENCY	N112AG	198.0	42.8
	N112AGT	471.5	31.3