

**DECISION MODEL FOR  
HYDROPONIC TOMATO PRODUCTION (HYTODMOD)  
USING UTILITY THEORY**

**A DISSERTATION**

**Presented in partial fulfillment of the requirements for  
the degree Doctor of Philosophy in the Graduate  
School of The Ohio State University**

by

**Amgad Hassan El-Attal, B.Sc., MS**

\* \* \* \* \*

**The Ohio State University**

**1995**

**Ph.D. Dissertation Committee:**

**T. H. Short, Ph.D. & Adviser**

**H. M. Keener, Ph.D.**

**R. P. Fynn, Ph.D.**

**C. C. Pasian, Ph.D.**

**Approved by:**



**Adviser  
Department of  
Agricultural Engineering**

copyright by

**Amgad Hassan El-Attal**

1995

**DEDICATION**

**To**

**My Parents,**

**My Wife Nevine, and**

**My Daughter Jana**

## ACKNOWLEDGMENTS

I express sincere appreciation to Dr. Ted Short for his guidance and advice throughout the research project. Special thanks are due to Dr. Peter Fynn for his valuable remarks and comments throughout the research. Gratitude is expressed to Dr. Harold Keener for his insight, support and encouragement. A particular thanks goes to James Brown, CropKing, Inc. and Dr. Robert McMahon, Agricultural Technical Institute, for their cooperation and assistance throughout the experiential study of the research. Also, I would like to thank Bert Bishop, Statistics laboratory of Ohio Agricultural Research and Development Center (OARDC), for his valuable suggestions and advice. The technical assistance of Michael Sciarini, Bill Kreider, and Roger Maas is greatly acknowledged.

## VITA

- March 25, 1963..... Born - Alexandria, Egypt
- 1984..... B.Sc., Agricultural Engineering  
Alexandria University,  
Alexandria, Egypt.
- 1984-1986..... Research Assistant, Agricultural  
Engineering Research Institution,  
Giza, Egypt.
- 1991..... M.S. in Agricultural Engineering,  
The Ohio State University,  
Columbus, Ohio

## FIELD OF STUDY

Major Field: Agricultural Engineering,  
studies in decision analysis, greenhouse production, hydroponics

## TABLE OF CONTENTS

<b>DEDICATION</b> -----	<b>ii</b>
<b>ACKNOWLEDGMENTS</b> -----	<b>iii</b>
<b>VITA</b> -----	<b>iv</b>
<b>LIST OF FIGURES</b> -----	<b>ix</b>
<b>LIST OF TABLES</b> -----	<b>xiii</b>
<b>CHAPTER I</b> -----	<b>1</b>
<b>INTRODUCTION</b> -----	<b>1</b>
1.1 Background-----	<b>1</b>
1.2 Objectives-----	<b>3</b>
<b>CHAPTER II</b> -----	<b>4</b>
<b>HYDROPONIC GROWTH STUDIES-EXPERIENTIAL</b> -----	<b>4</b>
2.1 Introduction-----	<b>4</b>
2.2 Greenhouse Growing Intensive Course-----	<b>4</b>
2.3 Growing a Tomato Crop Hydroponically-----	<b>5</b>
2.3.1 Greenhouse and Control-----	<b>5</b>
2.3.2 Plant Growing Technique-----	<b>5</b>
2.3.3 Air Temperature Control-----	<b>6</b>

2.3.4	Data Acquisition System	6
2.3.5	Dry-Bulb Temperature Measurement	7
2.3.6	Root Temperature Measurement	7
2.3.7	Short Wave Solar Radiation Measurement	8
2.3.8	Relative Humidity Control	8
2.3.9	Relative Humidity Measurement	8
2.3.10	CO <sub>2</sub> Measurement	8
2.3.11	Electrical Conductivity Measurement	9
2.3.12	Electrical Conductivity Adjustment	9
2.3.13	Hydrogen Ion Concentration Measurement	10
2.3.14	Hydrogen Ion Concentration Adjustment	10
2.3.15	Macro and Micronutrient Measurements	11
2.3.16	Irrigation Control	13
2.3.17	Cultural Practices	14
2.4	Experiential Growing Results	14
2.4.1	Leaf Analysis Results	14
2.4.2	Water Analysis Results	18
2.4.3	Feeding Nutrient Solution Analysis Results	19
<b>CHAPTER III</b>		<b>21</b>
<b>LITERATURE REVIEW</b>		<b>21</b>
3.1	Introduction	21
3.2	Hydroponic Tomato Growth Studies	21
3.2.1	Root Temperature	21
3.2.2	Electrical Conductivity	31
3.2.3	Hydrogen Ion Concentration	39
3.2.4	Relative Humidity	42
3.2.5	Air Temperature	49
3.3	Greenhouse Crop Growth Modeling	58

<b>CHAPTER IV</b> -----	<b>67</b>
DEVELOPMENT OF A DECISION MODEL-----	67
4.1 Introduction-----	67
4.2 Decision Model-----	67
4.2.1. The Main Program-----	70
4.2.2 The Growth Stage Subroutines-----	70
4.2.3. The Checkresults Subroutine-----	71
4.2.4 The Adjustment Subroutines-----	72
4.3 Applying the Utility Theory to the Prioritization Scheme-----	72
4.4 The Decision Tree-----	75
<b>CHAPTER V</b> -----	<b>77</b>
DEVELOPMENT OF GROWTH ACTIVITY FUNCTIONS-----	77
5.1 Introduction-----	77
5.2 Analysis of Literature-----	77
5.3 Growth Activity Functions-----	93
5.3.1 Hydrogen Ion Concentration of the Feeding Solution-----	93
5.3.2 Root Temperature-----	95
5.3.3 Air Temperature-----	98
5.3.4 Electrical Conductivity of the Feeding Solution-----	103
5.3.5 Relative Humidity-----	107
<b>CHAPTER VI</b> -----	<b>111</b>
VALIDATION OF DECISION MATRIX-----	111
6.1 Introduction-----	111
6.2 Brief Description of Chosen Experts-----	111
6.3 Priority Test for the Experts-----	113
6.4 Methodology of Analysis and the Scoring of Results-----	115



<b>CHAPTER VII</b>	<b>119</b>
<b>RESULTS AND DISCUSSION</b>	<b>119</b>
7.1 Introduction	119
7.2 Validity of Test Results	119
7.2.1 Matching Results with Experts	120
7.2.1.1 Hydrogen Ion Concentration of the Feeding Solution	122
7.2.1.2 Root Temperature	123
7.2.1.3 Air Temperature	126
7.2.1.4 Electrical Conductivity of the Feeding Solution	129
7.2.1.5 Relative Humidity	133
7.2.2 Sensitivity Analysis on Scoring Weights	136
7.2.3 The Statistical Analysis Results	137
<b>CHAPTER VIII</b>	<b>142</b>
<b>CONCLUSIONS</b>	<b>142</b>
<b>CHAPTER IX</b>	<b>144</b>
<b>RECOMMENDATIONS FOR FUTURE RESEARCH</b>	<b>144</b>
<b>LIST OF REFERENCES</b>	<b>146</b>
<b>APPENDIX A</b>	<b>153</b>
<b>EXAMPLE OF THE VALIDITY TEST GIVEN TO THE EXPERTS</b>	<b>153</b>

## LIST OF FIGURES

Figure 2.1 Leaf Analysis Results on March 30, 1994 (Vegetative Stage) of Experiential Studies of Tomato Growth.....	15
Figure 2.2 Leaf Analysis Results on April 18, 1994 (Early Fruiting Stage) of Experiential Studies of Tomato Growth.....	16
Figure 2.3 Leaf Analysis Results on August 30, 1994 (Mature Fruiting Stage) of Experiential Studies of Tomato Growth.....	17
Figure 4.1 Flow Chart of the Decision Model.....	68
Figure 4.2 The Decision Tree .....	75
Figure 5.1 Tomato Growth Activity Function for Hydrogen Ion Concentration from Germination and Early Growth Stage until Termination Stage for Producing Best Crop .....	94
Figure 5.2 Tomato Growth Activity Function for Root Temperature from Germination and Early Growth Stage until Seedling Stage for Producing Best Crop.....	96
Figure 5.3 Tomato Growth Activity Function for Root Temperature from Vegetative Stage until Termination Stage for Producing Best Crop .....	97

**Figure 5.4 Tomato Growth Activity Function for Greenhouse Air Temperature during Germination and Early Growth Stage for Producing Best Crop .....99**

**Figure 5.5 Tomato Growth Activity Function for Greenhouse Night Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop .....100**

**Figure 5.6 Tomato Growth Activity Function for Sunny Day Greenhouse Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop.....101**

**Figure 5.7 Tomato Growth Activity Function for Cloudy Day Greenhouse Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop.....102**

**Figure 5.8 Tomato Growth Activity Function for Feeding Solution Electrical Conductivity during Germination and Early Growth Stage for Producing Best Crop.....104**

**Figure 5.9 Tomato Growth Activity Function for Sunny Day Feeding Solution Electrical Conductivity from Seedling Stage until Termination Stage for Producing Best Crop.....105**

**Figure 5.10 Tomato Growth Activity Function for Cloudy Day Feeding Solution Electrical Conductivity from Seedling Stage until Termination Stage for Producing Best Crop .....106**

<b>Figure 5.11 Tomato Growth Activity Function for Greenhouse Air Relative Humidity during Germination and Early Growth Stage for Producing Best Crop.....</b>	<b>108</b>
<b>Figure 5.12 Tomato Growth Activity Function for Greenhouse Air Relative Humidity during Seedling Stage for Producing Best Crop.....</b>	<b>109</b>
<b>Figure 5.13 Tomato Growth Activity Function for Greenhouse Air Relative Humidity from Vegetative Stage until Termination Stage for Producing Best Crop.....</b>	<b>110</b>
<b>Figure 7.1 Tomato Growth Activity Function for Root Temperature from Germination and Early Growth stage until Seedling Stage for Producing Best Crop before and after Validation.....</b>	<b>124</b>
<b>Figure 7.2 Tomato Growth Activity Function for Root Temperature from Vegetative Stage until Termination Stage for Producing Best Crop before and after Validation .....</b>	<b>125</b>
<b>Figure 7.3 Tomato Growth Activity Function for Sunny Day Greenhouse Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop before and after Validation.....</b>	<b>127</b>
<b>Figure 7.4 Tomato Growth Activity function for Cloudy Day Greenhouse Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop before and after Validation.....</b>	<b>128</b>

<b>Figure 7.5 Tomato Growth Activity Function for Sunny Day Feeding Solution Electrical Conductivity from Seedling Stage until Termination Stage for Producing Best Crop before and after Validation .....</b>	<b>131</b>
<b>Figure 7.6 Tomato Growth Activity Function for Cloudy Day Feeding Solution Electrical Conductivity from Seedling Stage until Termination Stage for Producing Best Crop before and after Validation .....</b>	<b>132</b>
<b>Figure 7.7 Tomato Growth Activity Function for Greenhouse Air Relative Humidity during Germination and Early Growth Stage for Producing Best Crop before and after Validation .....</b>	<b>134</b>
<b>Figure 7.8 Tomato Growth Activity Function for Greenhouse Air Relative Humidity during Seedling Stage for Producing Best Crop before and after Validation.....</b>	<b>135</b>

## LIST OF TABLES

Table 2.1	The Macro and Micro Nutrients Composition of the Feeding Solution for Experiential Studies of Tomato Growth.....	12
Table 2.2	Irrigation Water Analysis Results for Experiential Studies of Tomato Growth.....	18
Table 2.3	Nutrient Solution Analysis Results for Experiential Studies of Tomato Growth.....	19
Table 5.1	Summary of the Root Temperature Studies for Greenhouse Grown Tomatoes.....	78
Table 5.2	Summary of the Electrical Conductivity Studies for Greenhouse Grown Tomatoes.....	81
Table 5.3	Summary of the pH Studies for Greenhouse Grown Tomatoes.....	85
Table 5.4	Summary of the Air Temperature Studies for Greenhouse Grown Tomatoes.....	86
Table 5.5	Summary of the Air Relative Humidity Studies for Greenhouse Grown Tomatoes.....	91

<b>Table 7.1</b>	<b>Number of Matching Agreements among Four Greenhouse Tomato Production Experts, and Between the HYTODMOD Model and the Experts Based on 25 Input Scenarios.....</b>	<b>121</b>
<b>Table 7.2</b>	<b>Sensitivity Analysis on Scoring Weights.....</b>	<b>136</b>
<b>Table 7.3</b>	<b>Statistical Analysis on the Compatibility of the Decision Model (HYTODMOD) Output with Each of the Four Expert Outputs. ....</b>	<b>138</b>

# CHAPTER I

## INTRODUCTION

### 1.1 Background

The ability to control greenhouse environments has resulted in the production of consistently high quality tomato crops by expert growers. The use of hydroponic growing systems has especially enhanced the opportunity for plant growth control. Hydroponics involves growing crops in a solution culture, or in a soilless medium such as rockwool or perlite which has a high holding capacity for both air and water. The main advantage of growing hydroponically is that the plant roots obtain minerals only from the solution supplied to them; therefore, less energy and growth are required to obtain the nutrients compared to plants grown in soil. Another advantage of hydroponics that there is less chance, when compared to growing in a soil, for plant roots to get infected by a disease.

In order to obtain high quality hydroponic crops, key tests and decisions must be conducted and made on a daily basis throughout the entire crop production. A key test in this study was defined as a measurable variable that was related to a controllable factor. The variables could have different recommended values from one growth stage to another. At all times, however, controlling the key test variables were critical to the growth of the highest quality crop.



Identifying the key tests as well as their optimum ranges are not sufficient in themselves to produce high yields of high quality fruit. Quite often the test result may not fall within the required optimum range. Many growers have insufficient knowledge of the kinds of adjustments that are needed to correct such test result. Also, sometimes there will be more than one unacceptable result from different tests at which time the grower will need to decide on the most critical ones and deal with them accordingly. Because the decision process is continuous, occurring daily (and sometimes hourly) over many months, all growers, regardless of their size and experience, make a significant number of decisions throughout the entire tomato production. Consequently, the chance for mistakes is highly probable. Thus, there is a tremendous opportunity for an integrated decision model that would guide the grower through tests that need to be conducted, decisions that need to be made, and practices that need to be performed on a timely basis. Such a model should reduce the chance for mistakes and save growers time and effort, thus making them more efficient and more able to produce high yield, high quality fruit.

## **1.2 Objectives**

The general objective of this research was to develop an integrated decision model for a hydroponic tomato grower that would prioritize by probability the necessary actions to produce high yield, high quality tomato fruit. This was done by achieving the following **specific objectives**:

- 1) Identify the necessary key tests to produce high yield, high quality fruit.
- 2) Identify the acceptable optimum ranges for the results of each test.
- 3) Identify the appropriate action required based on the results of the test.
- 4) Prioritize the necessary actions using the utility theory of decision analysis.
- 5) Develop a computer decision model to carry out objectives 1 - 4.
- 6) Validate the computer decision model with experts recommendations.

## CHAPTER II

### HYDROPONIC GROWTH STUDIES-EXPERIENTIAL

#### 2.1 Introduction

The first objective of this study in developing a hydroponic decision model was to identify key tests and actions necessary for producing high yield, high quality tomato fruit. The first two activities of this research were to attend a week-end grower school by CropKing, Inc., Medina, Ohio, and to do a tomato crop growing experience in a greenhouse, using hydroponic techniques. This chapter explains the CropKing school and the experiential study procedures. For the experiential study, the list of equipment used during the experiment is given. Also, the results of the experiential study are presented.

#### 2.2 Greenhouse Growing Intensive Course

When this research started, the researcher was a novice grower without any experience or background on growing greenhouse crops. In order to cover as much information as possible and to gain as much knowledge as possible about the growing process, a two day intensive course on growing hydroponic tomatoes was taken.

5

The course was offered by CropKing, Inc., Medina, Ohio, one of the most prominent companies nationwide in the area of hydroponics. The key subjects covered in the school included the different factors affecting successful production throughout the growing stages of a tomato crop. It especially included the cultural practices necessary to produce a high quality, high yielding crop. The classification of the hydroponic tomato production into five growing stages was learned from the CropKing school and used throughout this research. The widely experienced horticulturist of CropKing who instructed the course, continued to be a key source of information for producing a high quality crop throughout the experiential phase of this study.

### **2.3 Growing a Tomato Crop Hydroponically**

#### **2.3.1 Greenhouse and Control**

An experiential production experiment was carried out in the Select-A-Shade (SAS) greenhouse located at the Ohio Agricultural Research and Development Center (OARDC) in Wooster, Ohio. The greenhouse was designed at the OARDC to study energy requirements and to control solar radiation. The greenhouse floor area was 7.3m<sup>2</sup>.

#### **2.3.2 Plant Growing Technique**

Seeds of tomato cultivar 'Carusso' were sown on February 10, 1994 in small rockwool cubes of size 1.5". Plants were then transplanted into 3" rockwool cubes on March 8, 1994. On April 7, 1994, twenty-seven plants were transplanted into perlite bags at a plant density of 2.5 plant/m<sup>2</sup> with three plants per bag. Groups of three perlite bags

were placed on a greenhouse bench (4x3.5ft<sup>2</sup>). The experiment was conducted under Ohio solar light conditions.

### 2.3.3 Air Temperature Control

The air temperature inside the SAS greenhouse was controlled by the Greenhouse Environment Manager 3 (GEM3) computer software developed by the QCOM company. When the air temperature inside the SAS greenhouse fell below the air temperature set points, the QCOM system closed the outside vent and turned on the unit heaters 1 and/or 2 depending on the extent to which the SAS air temperature varied from the air temperature set points. In this case the recirculation fan would be on. When the air temperature inside the SAS was higher than the air temperature set points, the QCOM system opened the outside vent of the SAS greenhouse and the recirculation fan would be off. If the air temperature was still too high, the pellet roof of the SAS was used to shade the greenhouse.

### 2.3.4 Data Acquisition System

All of the measuring devices were connected to a Kaye Digistrip III 48 channel data logger, from Kaye Instruments, Inc., Bedford, MA. Each measuring sensor was connected to one of the channels. The data logger recorded the readings in mV, and then converted the readings into °C for the temperatures, into ppm for the CO<sub>2</sub>, into % for the

RH, and into  $Wm^2$  for short wave radiation. The data were then transferred to an MFE tape recorder from which data was loaded into a PC computer.

**2.3.5 Dry-Bulb Temperature Measurement**

The dry bulb temperature inside the SAS greenhouse was measured by two different systems. The QCOM control system measured the air temperature every minute through a solid state sensor, model HP-200A and recorded the average of values every 15min. The dry bulb temperature was also measured by an aspirated 0.04" stainless steel type (T) thermocouple. One of the thermocouple terminals was attached to the Kaye Digistrip III and the other one was placed inside an aspirated housing made by PRIVA company. The PRIVA unit was located in the middle of the greenhouse immediately above the plants.

**2.3.6 Root Temperature Measurement**

A type (T) thermocouple was used to measure the root temperature throughout the experiment. In the beginning of the experiment the thermocouple was inserted inside one of the 1.5" rockwool cubes to monitor the temperature inside the media where the tomato seeds were germinating. After the plants were transplanted into 3" rockwool cubes, the thermocouple was relocated to the large cube. Finally, after the large cubes were transplanted into the perlite bags, the thermocouples were inserted into the bag to continue monitoring the temperature of the perlite media where the roots were growing.

### **2.3.7 Short Wave Solar Radiation Measurement**

The measurements of the total short wave radiation were measured by an Eppley radiometer, model 8-48 from Eppley Laboratory Inc., Newport, R.I. One of the radiometers was located outside the SAS greenhouse, and the other one was located in the middle of the SAS greenhouse above the plant canopy.

### **2.3.8 Relative Humidity Control**

The relative humidity (RH) inside the SAS greenhouse was controlled by the GEM3 computer software from the QCOM company. When the RH inside the SAS greenhouse fell below the RH set points, the QCOM system turned on a humidifier that raised the RH to the optimum level.

### **2.3.9 Relative Humidity Measurement**

A digital humidity analyzer, model 911 Dew ALL from EG&G Inc., Burlington, MA, was used to measure the dew point temperature inside the SAS greenhouse. The data acquisition system was programmed to calculate the RH from the dew point temperature and the dry bulb temperature readings.

### **2.3.10 CO<sub>2</sub> Measurement**

A CO<sub>2</sub> analyzer, model Lira 202 from Mine Safety Appliance, Pittsburgh, PA, was used to measure the CO<sub>2</sub> concentration inside the SAS. The CO<sub>2</sub> measurements were recorded by the Kaye Digistrip III.

### **2.3.11 Electrical Conductivity Measurement**

The electrical conductivity (EC) of the feeding solution was measured using an EC meter from the Cole Palmer Company. Also the EC of the tomato growing media was measured using the same EC meter. In the beginning of the experiment the growing media consisted of small rockwool cubes followed by large rockwool cubes. The large cubes were later transplanted into perlite bags. Since the EC of the solution inside the growing media is very critical for proper growth of the plants, the EC was checked daily by sampling from all the rockwool cubes, and then from all the perlite bags. If the EC value did not fall within the acceptable EC range for the given growing stage, a proper measure of adjustment was carried out as will be described in the next section.

### **2.3.12 Electrical Conductivity Adjustment**

- If the EC of the feeding solution was lower than the specified optimum level then fertilizer concentrate was added carefully to the nutrient solution in order to bring the EC up to the desired level. The amount of concentrate added was recorded for the following solution preparation.
- If the EC of the feeding solution was too high, the solution was diluted by carefully adding water to the feeding solution. The amount of water added was recorded for the following solution preparation.
- If the EC in the cubes or perlite bags was too high, then the EC level of the feeding solution was checked first and adjusted if necessary. If the EC level of the feeding



solution was correct, the volume of irrigation was increased to leach the growing media and eliminate the accumulated concentrates. During the leaching process, samples were taken from the growing media to check whether the desired EC level was reached.

### **2.3.13 Hydrogen Ion Concentration Measurement**

The pH of the feeding solution was measured using a pH meter from the Cole Palmer Company. Also the pH of the tomato growing media was measured using the same pH meter. Since the pH of the solution inside the growing media is very critical for proper growth of the plants, the pH was checked regularly by sampling from all the rockwool cubes and then from all the perlite bags. If the pH value did not fall within the acceptable pH range for the given growing stage, a proper measure of adjustment was carried out as will be described in the next section.

### **2.3.14 Hydrogen Ion Concentration Adjustment**

- If the pH of the feeding solution was lower than the specified optimum level, potassium hydroxide (KOH) solution was added carefully to the feeding solution. The amount of KOH added was recorded for the following solution preparation.
- If the pH of the feeding solution was too high, then sulphuric acid ( $H_2SO_4$ ) was added carefully to the feeding solution. The amount of the acid added was recorded for the following solution preparation.

- If the pH in the cubes or perlite bags was too high, the pH level of the feeding solution was checked and adjusted if necessary. If the pH level of the feeding solution was correct, the volume of irrigation was increased to leach the growing media with the pH corrected solution. During the leaching process, samples were taken from the growing media to check whether the desired pH level was reached.

### **2.3.15 Macro and Micronutrient Measurements**

Water analysis was done regularly in the Research Extension Analytical Laboratory (REAL lab), located at the OARDC in Wooster, OH. The amount of each macro- and micro-nutrient element needed for the feeding solution was determined based on the lab results.

A sample from the feeding solution was also taken regularly for a macro- and micro-nutrient analysis that was conducted in the REAL lab. A tomato leaf analysis was conducted regularly to check the macro- and micro-nutrient distribution in the tomato plant. The sample was taken from the leaf and petiole below the highest cluster with green, golf-ball-sized fruit. The sample position was very critical because, if the sample was taken from above the right position then some of the nutrients like Calcium would not fall within the expected range. Also, samples were not to be taken from a place near the base of the plant, as this could indicate the presence of some nutrients that could be missing from the current nutrient solution. Missing nutrients were most apparent in an analysis of a relatively new leaflet.

Two different nutrient programs were used throughout the experiment. The first nutrient program, called the normal program, started immediately after the seeds were sown and continued until blossoms appeared on the second cluster. The second program, called the boosted program, was put into effect after the appearance of the second cluster and continued to the conclusion of the experiment. Table 2.1 shows the composition of the macro- and micro-nutrients applied during the first and the second programs.

Table 2.1 The Macro and Micro Nutrients Composition of the Feeding Solution for Experiential Studies of Tomato Growth

Element	ppm for the normal program*	ppm for the boosted program**
Nitrogen (N)	200	275
Phosphorous (P)	50	50
Potassium (K)	350	440
Calcium (Ca)	185	225
Magnesium (Mg)	45	60
Iron (Fe)	1.05	1.05
Manganese (Mn)	0.75	0.75
Zinc (Zn)	0.33	0.33
Copper (Cu)	0.1	0.1
Boron (B)	0.35	0.35
Molybdenum (Mo)	0.04	0.04

- \* Normal program: Started immediately after the seeds were sown and continued until blossoms appeared on the second cluster.
- \*\* Boosted program: Started from the appearance of blossoms in the second cluster and continued to the conclusion of the experiment

### 2.3.16 Irrigation Control

Drip irrigation was used for irrigating the tomato plants inside the SAS greenhouse. Irrigation scheduling was controlled by the GEM3 computer software developed by the QCOM company. The GEM3 software was programmed to control a timing device, called a timed irrigation commander, based on a predetermined irrigation cycle. The timed irrigation commander was connected to a water pump immersed in a feeding tank which supplied the feeding solution to the irrigation tubes and then to the perlite bags through drip emitters.

During the germination stage, a warm nutrient solution (pH corrected 5.5 to 5.8) (with an EC of 1800  $\mu$ mhos/cm) was applied on the top of the rockwool cubes. The irrigation emitters were calibrated to give 56.7 gm/plant/hr during the daylight hours in the beginning of the experiment, then 113.4 gm/plant/hr during the daylight hours after the plants were established in the bags. Beginning at the vegetative phase, the feeding level was sometimes increased to 141.8 and 155.9 gm/plant/hr, depending on the growth stage and the lighting conditions. This was determined by regularly checking the moisture of the bags.

At the beginning of the experiment, the emitters were placed directly on the rockwool cubes. After the cubes were transplanted into the perlite bags, the emitters were relocated to the perlite bags.

### **2.3.17 Cultural Practices**

The following cultural practices were carried out regularly once the rockwool cubes was transplanted to the perlite bags:

1. Suckering started once side shoots came out.
2. Pollinating, using an electric pollinator started when the first flower opened.
3. Supporting the plant started when the plants were transplanted into the bags.
4. Clipping, cluster pruning, and leaf pruning was done as needed according to CropKing recommendations.

## **2.4 Experiential Growing Results**

Throughout the experiential crop growing experiment, a number of analyses were conducted to carefully monitor the growth of the tomato crop, and to correct any nutrient or disease problem as needed. The experience and results of the analyses were a key source in formulating Growth Activity Functions (GAF) used in the decision model. The GAFs are explained later in the dissertation.

### **2.4.1 Leaf Analysis Results**

Regularly conducted leaf analyses showed the macro- and micro-nutrient composition in the tomato plant. The analyses were conducted at the Research Extension Analytical Laboratory (REAL) at the Ohio Agricultural Ohio Agricultural Research and Development Center (OARDC). The first leaf analysis was conducted during the vegetative stage on March 30, 1994 when a yellowish coloring was observed on the edge of some upper leaves. The results of the analysis indicated a high level of K, a deficiency.

in Ca, and a low level of Mg (Figure 2.1). There were sufficient levels of the remaining macro- and micro-nutrients. Following this leaf analysis, the normal nutrient program suggested by CropKing was used. Figure 2.2 shows the results of the next leaf analysis during early fruiting stage conducted on April 18, 1994 where both the Mg and K levels became sufficient and the Ca level remained insufficient.

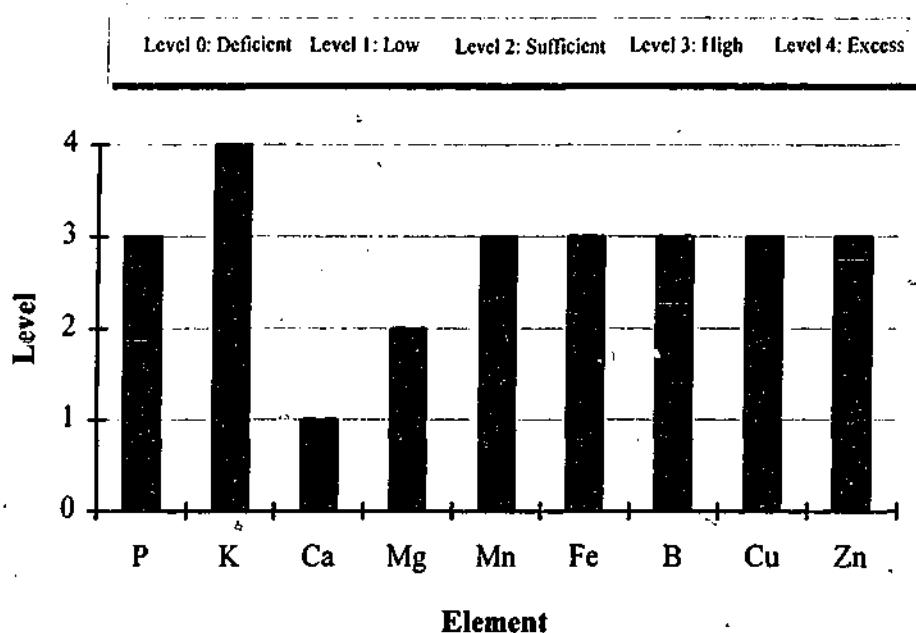


Figure 2.1 Leaf Analysis Results on March 30, 1994  
(Vegetative Stage) of Experimental Studies  
of Tomato Growth

There were two causes identified for the Ca deficiency in the plants. Some of the plants were infected with crown root rot disease and the leaf samples were taken at an inappropriate location. The disease problem was corrected using the chemical Benlate

and the sampling problem was corrected by taking the samples of the leaf and petiole below the highest cluster with green golf-ball sized fruit as instructed by the REAL lab. The correction of both problems is clearly demonstrated in Figure 2.3 with a leaf analysis during mature fruiting stage on August 30, 1994 indicating sufficient levels of all macro- and micro-nutrients.

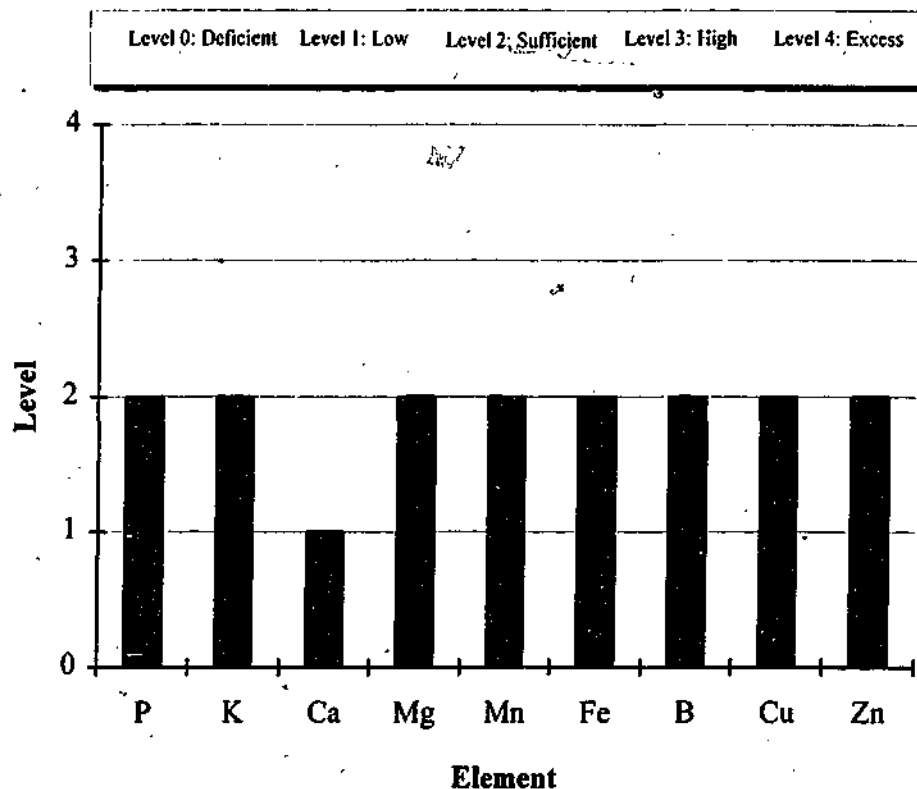


Figure 2.2 Leaf Analysis Results on April 18, 1994  
(Early Fruiting Stage) of Experiential  
Studies of Tomato Growth

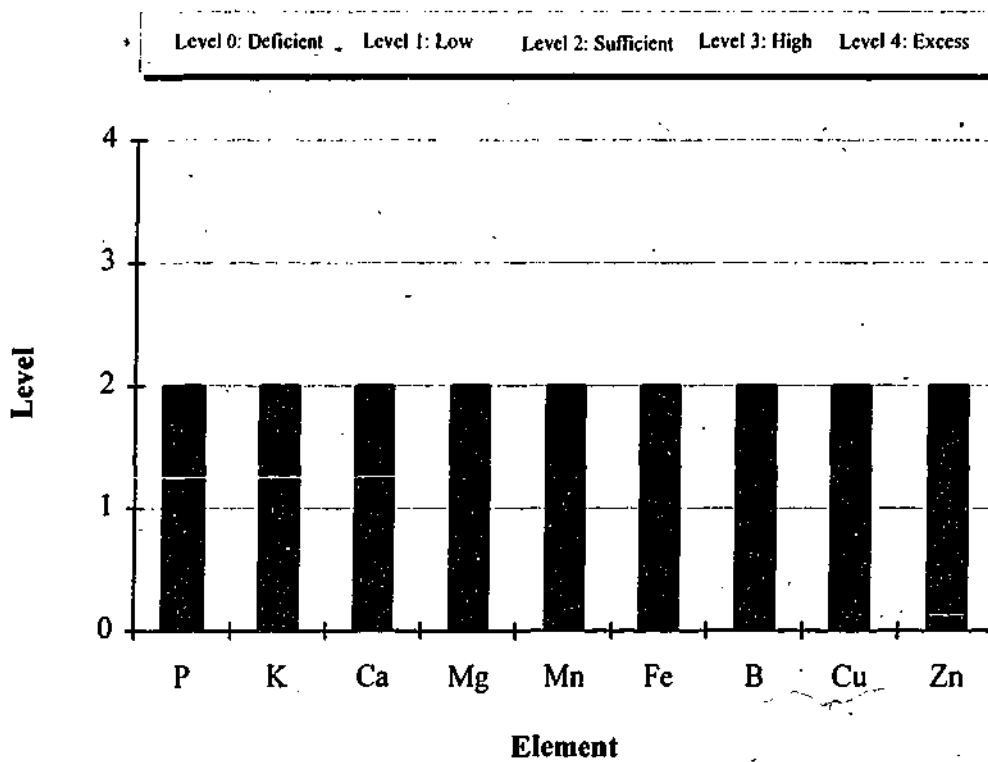


Figure 2.3 Leaf Analysis Results on August 30, 1994  
(Mature Fruiting Stage) of Experiential  
Studies of Tomato Growth



### 2.4.2 Water Analysis Results

The water used in the nutrient solution throughout the experiment was analyzed monthly at the REAL lab. Table 2.2 shows the water analysis results for three consecutive months where the composition of the macro- and micro-nutrients of the feeding solution were determined based on these results. The pH for the water for the last two months shown was 8.1 and 7.2 respectively and the EC for the water for the same two months was 670 and 660  $\mu$ mhos/cm respectively.

Table 2.2 Irrigation Water Analysis Results for Experiential Studies of Tomato Growth

Element	Value (ppm) on 04/18/94	Value (ppm) on 05/16/94	Value (ppm) on 06/06/94
Phosphorous (P)	< 0.10	< 0.10	0.10
Potassium (K)	1.87	3.34	1.80
Calcium (Ca)	73.90	72.00	74.70
Magnesium (Mg)	25.60	26.90	26.70
Sodium (Na)	21.20	26.90	34.00
Iron (Fe)	< 0.06	< 0.06	< 0.06
Manganese (Mn)	< 0.01	< 0.01	0.01
Zinc (Zn)	0.03	< 0.004	0.055
Copper (Cu)	< 0.02	< 0.02	0.08
Boron (B)	0.09	0.10	0.15
Nitrate-Nitrogen		1.00	< 1.00
Sulphate-Sulfur	21.00	19.00	17.00
Chloride	55.00	61.00	71.00

### 2.4.3 Feeding Nutrient Solution Analysis Results

The feeding nutrient solution was analyzed regularly at the REAL lab. The first column of Table 2.3 shows the concentration of the nutrient solution for the normal feeding program as detailed in Table 2.1. The second and third columns of Table 2.3 show the concentrations of the nutrient solution for the boosted feeding program on April 28 and May 16, 1994 as detailed in Table 2.1.

Table 2.3 Nutrient Solution Analysis Results for Experiential Studies of Tomato Growth

Element	Value (ppm) on 04/18/94	Value (ppm) on 04/28/94	Value (ppm) on 05/16/94
Phosphorous (P)	52.40	36.10	29.10
Potassium (K)	348.04	303.49	218.15
Calcium (Ca)	195.90	154.30	168.80
Magnesium (Mg)	47.60	42.10	42.30
Sodium (Na)	4.80	11.60	38.60
Iron (Fe)	0.90	11.48	0.42
Manganese (Mn)	0.84	0.69	0.51
Zinc (Zn)	0.397	0.448	0.297
Copper (Cu)	0.12	0.10	0.09
Boron (B)	0.40	0.29	0.38
Nitrate-Nitrogen	250.00	185.00	165.00
pH	5.8	5.8	5.8
EC ( $\mu$ mhos/cm)		2280	1980

The nutrient solution analyses showed two key results. First, it showed the composition ratio of the macro- and micro-nutrients of the feeding solution for each analysis and whether these ratios were fed as recommended for both the normal and the boosted programs. Second, it showed the pH and the EC of the feeding solution, respectively. Although the pH and the EC results do not represent the kind of daily results expected for such tests, they confirmed the maintenance of the optimum recommended levels.

## **CHAPTER III**

### **LITERATURE REVIEW**

#### **3.1 Introduction**

The key tests identified from the CropKing grower school and the experimental study included root temperature, electrical conductivity of the feeding solution and pH of the feeding solution, greenhouse air relative humidity, and greenhouse air temperature. This section reviews the studies conducted by other researchers in the field on the identified key tests. It also investigates the significance of those tests in establishing optimum growing ranges to produce high yield, high quality fruit.

#### **3.2 Hydroponic Tomato Growth Studies**

##### **3.2.1 Root Temperature**

The body of research done on root temperature (RT) reveals that it has a significant influence on plant growth and development, particularly in terms of dry weight gain, plant height, root extent and form, leaf expansion and form, flowering, and fruiting. There have also been several studies done on the influence of RT on the processes of photosynthesis, respiration, water absorption, and transpiration.

Root temperature was even studied as a means of overcoming the disadvantages of reducing air temperature in greenhouses. Air temperature was reduced to save fuel, but both growth rates and fruit harvesting were delayed. The following summary of key studies describe the optimum growing ranges for the RT necessary for producing a high quality crop.

Jones et al (1978) found that tomato crop productivity could be maintained under reduced night air temperature (9°C) when roots were warmed up to 24°C. Also, Gosselin and Trudel (1983) found that maximum tomato growth was obtained at a higher root temperature when night air temperature was reduced from 21 to 12°C,

Abdelhafeez et al. (1971) studied the effect of soil and air temperature on growth, development and water use of tomatoes in two series of trials. In one trial, tomato plants were grown in a glasshouse without air temperature control at soil temperatures ranging from 14 to 29°C. In the other trial tomato plants were grown in phytotron glasshouses at constant air temperatures of 17, 21, and 25°C and at soil temperatures ranging from 12 to 30°C. The experiment started on the first week of April, and the treatments were applied three weeks after sowing. Growth was reduced at soil temperatures below 20°C, whereas the differences between the effects of soil temperatures in the range of 20°C to 30°C were only small and irregular. The authors mentioned that this result agreed with that of Fujishige and Sugiyama (1968), whereas Abdel Rahman et al. (1959b) reported a linear increase of leaf area with increasing soil temperatures between 17 and 30°C. An air temperature of 17°C also reduced growth during this period, compared with 21 and 25°C.

They also concluded that generative (the trusses with flowers and fruits) development was not generally influenced by soil temperature; a low air temperature (17°C) resulted in a late, but relatively rich flowering. After three weeks, there were no open flowers in the glasshouse and in the phytotron compartment with an air temperature of 17 °C. At air temperatures of 21 and 25°C, the percentage of open flowers in the first truss was 15 and 50, respectively.

The authors also found that during the last three weeks, the total dry-weight increase was not affected by the soil temperature and only slightly by the air temperature, being relatively low at 17°C. They concluded that there was an increased earliness at higher air temperatures. A greater part of the dry matter produced was used for fruit development, resulting in a strongly reduced vegetative growth at the higher air temperatures. As a consequence, plants at 21 and 25°C showed relatively thin stems and the yielding capacity was reduced. They added that constant air temperatures of 21°C or higher forced the tomato plants into such a quick development that a desirable balance between vegetative and generative growth was lost. They added that a similar effect of air temperature on earliness and capacity was reported by Abdelhafiez and Verkerk (1969). The authors also reported that at 22°C, the plants apparently could maintain a favorable water balance during the day without stomatal closure.

Hurewitz and Janes (1983) studied the effect of altering the root-zone temperature on growth, translocation, carbon exchange rate, and leaf starch accumulation in the tomato. They grew tomato seedlings hydroponically at constant root temperatures

ranging from 10 to 38.7°C for a 2-week period commencing with the appearance of the first true leaf.

The tomato plants showed an increase in growth as the root temperatures increased from 10°C to 30°C. They observed a sharp increase in growth when plants were grown with a root-zone temperature of 15.6°C as compared to 12.8°C. Plants grown at root-zone temperatures of 18.3 °C and below had thicker darker green leaves with increasing purplish coloration on the underside. Their roots were short, thick, and bunched as opposed to plants grown at warmer root zone temperatures (26.1 °C and above) where roots were long, thin and profusely branched. The differences in leaf morphologies were reflected by the higher specific leaf areas ( $\text{dm}^2 / \text{g}$  dry weight) from plants grown with a root-zone temperature of 30 °C as opposed to 15.6 °C. They cited Cooper (1973) as he attributed the effect of root-zone temperature on the growth response of tomato seedlings to the partitioning of dry matter between the root and shoot during germination and the first true leaf development.

The authors also mentioned that an environment which provides for satisfactory root growth should also benefit the shoot growth. Cool root-zone temperatures are capable of inhibiting and warm temperatures are capable of stimulating plant growth when air temperatures are not limiting to growth because vital, temperature-dependent processes which occur in the root also exert control over the shoot.

The authors concluded that root zone temperature had an indirect effect on the carbon exchange rate since plants grown in higher root zone temperatures up to 30°C had

greater leaf areas. The higher carbon exchange rate leaves were assumed to be more photosynthetically active than leaves of plants grown at warmer or cooler root-zone temperatures. They reported that roots of plants grown at excessively warm root-zone temperatures (above 32.2°C did not live if they remained in direct contact with the nutrient solution. The authors concluded that the optimal root-zone temperature for seedling growth based on fresh and dry weight as well as leaf area was 30°C.

Gosselin and Trudel (1984) studied the interactions between root-zone temperature and light levels on growth, development and photosynthesis of *Lycopersicon esculentum* mill. cultivar 'Vendor'. They also related these findings to crop productivity and plant photosynthesis. Six-week old tomato plants were subjected to 5 root-zone temperatures ranging from 12 to 36°C (12, 18, 24, 30, and 36°C, and four light levels in a factorial design. At the end of the experiment, fresh and dry weight of shoots and roots were determined and the number and the weight of fruits for each of the first 2 clusters were recorded.

They observed large increases in shoot dry weight, leaf area and fruit development with soil temperatures up to 24°C when plants were grown under high light conditions. Shoot growth and fruit weight were reduced at a 24°C root temperature under low light conditions. It was suggested that this may account for flower abscission and poor fruit set observed in some soil temperature studies conducted in the winter months. They also suggested that low tomato yields may have resulted from poor lighting conditions. When soil temperature rose above 17°C



Maletta and Janes (1987) studied the interrelation of root and shoot temperatures on dry matter accumulation and root growth in tomato seedlings. They conducted three separate experiments in which tomato seedlings were grown at root-zone temperatures of 21, 26.5, and 32°C. Each experiment differed in the air temperature (11, 16, or 21°C) of the growth chamber. Optimum root temperature, as indicated by dry weight, was 26.5°C except at the lowest air temperature (11°C) where it was 32°C. Optimum root temperature, as indicated by root length, was 26.5°C at all air temperatures. The rate of increase in root length was reduced at the lowest air temperature (11°C) and when root temperature was at 32°C. Relative growth rate was decreased at the lower air temperatures and when root temperature was 32°C. Air temperature had a greater effect than root temperature on relative growth rate except when the root temperature was above 26.5°C.

The authors also mentioned that their data supports the hypothesis that, once the root system is established, air temperature may become important for controlling top growth processes. They speculated that the adverse effect which the 32°C root temperature had on plant growth at 16°C and 21°C air temperature may be related to the reduced rate of root elongation at that root temperature.

They also said that root zone heating may be useful in optimizing growth at a given air temperature. However, they mentioned that maintaining higher root temperatures is unlikely to offset the growth limitations at lower air temperatures except for early in the season, and continuous high root temperatures were detrimental to

growth. They added that the interrelationship of root and shoot activity ultimately determines the outcome of plant growth, so the temperature environment of each component is important.

Cornillon (1988) studied the influence of root temperature on tomato growth and nitrogen nutrition. Young tomato plants were grown in nutrient solution at constant temperatures of 12 and 22°C. Seeds of tomato were sown on September 20 and germination took place between eight and ten days later. Both treatments of 12 and 22°C root temperatures were applied between the October 19 and November 7.

The author found that the tomato reacted strongly to the change in root temperature from 22 to 12°C; plant dry weight and water uptake were less than 70% of that observed at 22°C. He cited that Cooper in 1973 implied that the increase of root temperature acts favorably on the water and nutrients absorption.

The author related the change in growth between 12 and 22°C to a change in the plant nitrogen nutrition.  $\text{NO}_3$  accumulated in the root, showing that no substantial change occurred in the nitrate uptake when the root temperature was low. Also, he mentioned that the root nitrate reductase activity increased when the temperature decreased because the  $\text{NO}_3$  accumulated in the root. He cited Gosselin et al (1984) as one who had similar results.

Kennedy and Pegg (1989) studied the effect of root zone temperature on root rot symptom development in tomato cultivars Counter and Calypso grown in rockwool culture. Both tomato cultivars were sown in November and grown in blocks and watered

with a nutrient solution with pH of 6 and EC of 2500  $\mu\text{mhos/cm}$ . After the emergence of the first truss, plants were placed on 30 cm wrapped rockwool slabs (1 plant/slab). Vegetative growth was restricted under low light conditions by increasing the conductivity of the nutrient solution to 6000  $\mu\text{mhos/cm}$ . The pH and the conductivity were monitored daily and maintained at 6000-6500 and 6000  $\mu\text{mhos/cm}$ . Glasshouse air temperature was maintained at 18-20°C during the day and 14-16°C at night.

The plants were inoculated after developing nine trusses with *Phytophthora cryptogea*. After three days incubation at an ambient temperature, continuous block and slab temperatures of 15 and 25°C were imposed. They concluded that both cultivars, maintained at 15°C, developed acute aerial symptoms and subsequently died. Plants at the higher temperature remained symptomless for the three month duration of the experiment. They added that the root zone temperatures affected disease development in two ways: by altering root growth in host plants and by reducing inoculum production by the pathogen.

Tindall et al. (1990) studied the effect of root zone temperature on nutrient uptake of tomato. They grew tomatoes in growth chambers under six root zone temperature treatments: 10, 15.6, 21.1, 26.7, 32.2, and 37.8°C. The treatments were applied two weeks after the seedlings reached 8 cm in height and lasted for two weeks. Ambient air temperature was kept at 21.1°C. All treatments received the same nutrient concentrations. Light intensity in the chamber was kept at 390  $\text{mE m}^{-2} \text{s}^{-2}$  with a light/dark period of 14/10 hours. Solution samples were taken at the end of each week to

determine nutrient uptake. Plant height and water uptake were measured daily and solution pH was monitored every other day. The pH of the solution was controlled at  $5.8 \pm .03$ . The authors reported that the majority of macro- and micro-nutrients showed a trend in increased uptake from 10 to 26.7°C, with a steady decrease in uptake for all nutrients at higher temperatures. Tissue analyses showed that low levels of N were found in the 10 and 37.8°C treatments while all other treatments had sufficient levels. Both K and Mg had significantly lower levels at the 10, 15.5, and 37.8°C treatments. Also, the tissue analysis showed that P and K was significantly lower at 10, 15.5, and 37.8°C. Tissue content of Fe, Mn, and Mo showed no difference among treatments while Zn was significantly lower (but not deficient) at 37.8°C, B and Cu were significantly lower (but not deficient) at 10°C. They added that temperatures less than 20°C and above 30°C probably greatly impair nutrient absorption and water uptake. They also concluded that nutrient uptake for each element generally peaked at 26.7°C.

Root dry weight increased significantly with increased temperature until 26.7°C and then steadily decreased. Roots at 10°C showed poor elongation with somewhat larger diameter roots, but had a smaller number of roots. At 15.5°C, roots were slightly more elongated but had considerably more density. There was little visible difference between roots at 21.1 and 26.7°C, both being very dense with good elongation. In the 32.2°C treatment, root density was approximately the same as in the two lower temperature treatments, but with 50% less elongation. Roots at 37.8°C were similar in density and elongation to 10°C, but were very fine with very little branching and dark in

color. Shoot dry weight followed the same pattern as the roots. Shoot elongation was similar at intermediate temperatures, but sharply reduced at 10 and 37.8°C. The height of the plants at the conclusion of the experiment was significantly affected by temperature. The authors believed that this was due to the effect of temperature on physiological (enzymatic) factors of plant growth and on nutrient uptake.

Using regression analysis the authors found the optimal temperature for plant growth, water use, and root response to be between 21.1 and 26.7°C. They also concluded that the optimum temperature was approximately 25°C for uptake of the majority of mineral elements and all measured plant growth responses (Root and shoot dry weight, rate of shoot growth, plant height, and water use).

Abu Hadid (1991) recommended the optimum root temperature during the germination and seedling phase to be between 22 and 25°C. During the vegetative phase, he recommended an optimum level between 15 and 18°C. During the early and mature fruiting phase, he recommended the root temperature to be between 16 and 20°C.

CropKing, Inc. (1993) recommended the optimum root temperature range during the germination phase to be between 25 and 26.1°C, during the seedling phase to be between 19 and 20°C, and during the vegetative, early and mature fruiting phases to be between 21 and 22.2°C. They recommended a minimum root temperature of between 16.7 to 17.2°C and a maximum root temperature of 25.6°C.

### 3.2.2 Electrical Conductivity

Several studies examined the effect of electrical conductivity (EC) on the growth and yield of hydroponic tomatoes throughout the different growing stages. All verified the significance of EC on the production of a high quality crop.

Cooper (1972) studied the influence of container volume, solution concentration, pH, and aeration on dry matter partitioning by tomato plants in water culture. Seeds of cultivar Minibelle were sown on October 7. The author observed that reducing the solution concentration reduced the proportion of the total dry matter partitioning in the roots during the first two weeks of seedling growth, but subsequently increased it slightly. He also found that the concentration of the nutrient solution did affect partitioning in young tomato plants. The more dilute of two solutions (one was full strength and another was half strength) increased the proportion of dry matter going to the cotyledons, primarily at the expense of the roots, until approximately 30 days after sowing. Subsequently, a slightly higher proportion of the total dry matter was found in the roots in the more dilute solution. This increase in the proportion in the roots was achieved initially at the expense of the leaves, and subsequently at the expense of the stem.

Papadopoulos and Rendig (1983) studied the interactive effects of salinity and nitrogen on growth and yield of tomato. After one month from sowing, the plants were irrigated with basal nutrient solution of EC of 1000  $\mu\text{mhos/cm}$  for 15 days. The plants were subsequently grown in nutrient solutions containing 8, 64, or 120 ppm of  $\text{NO}_3\text{-N}$  with salinity levels of 1000, 5000, and 9000  $\mu\text{mhos/cm}$ . The authors observed a positive

response of plants to increasing levels of N at the lowest initial salinity level of 1000  $\mu\text{mhos/cm}$ . At the higher initial salinity levels of 5000 and 9000  $\mu\text{mhos/cm}$ , increasing N was ineffective in counteracting adverse effects on growth and yield caused by the presence of enhanced salt concentrations of the nutrient solution.

Costa et al. (1986) studied the influence of saline irrigation on tomato under protected cultivation. They cultivated six hybrids and 48 highly homozygotic lines in Spain under a non heated polyethylene plastic-house. Two repetitions were carried out: one of them was irrigated with sweet water (water without salinity problems) of 750  $\mu\text{mhos/cm}$  concentration, and the other one with well water (salt water) of 3076  $\mu\text{mhos/cm}$  concentration. Seed beds were set in December and transplanted into the greenhouse in February. Saline water irrigation produced a 42% average production decrease. Average fruit weight and fruit number, were not equally influenced; while saline water produced a 33% decrease on average fruit weight, fruit number were only reduced by 12%.

The use of saline water reduced the percentage of hollow fruits from 6% to 0% as well as fruit vascular necrosis from 18% to 2%. However, the incidence of blossom-end rot increased, particularly on two of the hybrids. Saline irrigation also affected vegetative development, reduced height, vigor and stem thickness.

Ehret and Ho (1986) studied the effects of salinity on dry matter partitioning and fruit growth in tomatoes grown in nutrient film culture. Seeds of tomato cultivar Marathon were sown in peat-sand on three occasions. Seedlings were transferred to

cubes of rock wool and placed in the nutrient film techniques (NFT) gullies when the buds of the first truss were just visible. Two gullies, each containing 15 plants were used for each salinity treatment. Salt concentrations in the nutrient solution with an EC from 2000 to 17000  $\mu\text{mhos/cm}$  were selected to investigate effects of salinity both below and above a typical grower level (3000-8000  $\mu\text{mhos/cm}$ ). High EC values were obtained by adding more quantity of a concentrated solution containing  $\text{KNO}_3$  (100 g/l) and  $\text{Ca}(\text{NO}_3)_2$  (100g/l). A minimum day temperature of 20°C, with venting at 21°C, and a minimum night temperature of 16°C were maintained and the pH was maintained at 5.8.

They observed that when the EC of the nutrient solution was in the range of 2000, 4000, and 6000  $\mu\text{mhos/cm}$ , neither the total plant dry weight nor the distribution of dry matter in fruit, shoot and roots were affected. However, when the EC was 10000  $\mu\text{mhos/cm}$ , total plant dry weight was reduced by 19% of that at 2000  $\mu\text{mhos/cm}$ . The proportional partitioning of dry matter into various organs was unaffected. The proportion of total plant weight in fruit was only reduced slightly at 17000  $\mu\text{mhos/cm}$ .

They also concluded that the increase in fruit fresh weight was markedly reduced by high solution conductivities (12000 and 17000  $\mu\text{mhos/cm}$ ) and the fresh weight of mature fruit grown at 17000  $\mu\text{mhos/cm}$  was 40% less than that of fruit grown at 2000  $\mu\text{mhos/cm}$ . They added that the dry matter accumulation by individual fruit was not affected by salinity resulting in a high percentage of dry matter for fruit growing with high salinity.



Bruggink et al. (1987) studied the effects of different day and night nutrient solution osmotic pressure on growth, and water potentials of young tomato plants in soilless culture. A constant normal (2000  $\mu\text{mhos/cm}$ ) and a constant relatively high concentration (6000  $\mu\text{mhos/cm}$ ) were compared to: a low concentration in day-time (300  $\mu\text{mhos/cm}$ ) combined with a high concentration at night (10000  $\mu\text{mhos/cm}$ ), and to a high concentration in day-time (10000  $\mu\text{mhos/cm}$ ) combined with a low concentration at night (300  $\mu\text{mhos/cm}$ ).

Tomato seeds were germinated in sand. After 7 days, seedlings were transplanted to pots with expanded clay, and placed in a nutrient solution (EC = 2000  $\mu\text{mhos/cm}$ ) to a depth of 2 cm. After 20 days, the plants were removed from the pots and distributed over 4 NFT gullies, with each gully representing one treatment. Higher EC values were obtained by adding more nutrients in the same proportion to the solution. The pH of the solution was maintained around 6.0. They found that vegetative growth, measured as fresh weight, dry weight and leaf area were stimulated by a low concentration in day-time (300  $\mu\text{mhos/cm}$ ) and by a high concentration at night (10000  $\mu\text{mhos/cm}$ ). There were no significant differences in the other three treatments.

Charbonneau et al. (1988) studied the influence of electrical conductivity of the nutrient solution on growth and yield of greenhouse tomatoes in NFT. Tomato plants were cultivated in an NFT system and subjected to three electrical conductivities (2000, 6000 and 10000  $\mu\text{mhos/cm}$ ) of a complete nutrient solution distributed continuously or intermittently until the setting of the second truss. The tomatoes were seeded on April

15, 1985 and seedlings were transplanted seven days later to rockwool blocks. Four weeks after seeding, the plants were placed in three recirculating nutrient film systems. The nutrient solutions temperature was kept at 25°C, and the pH at 6.2. The EC of 6000 and 10000  $\mu\text{mhos/cm}$  were formed by adding N-NO<sub>3</sub>, K, Ca, and Mg to the nutrient solution at 2000  $\mu\text{mhos/cm}$ .

The authors reported that raising EC from 2000 to 10000  $\mu\text{mhos/cm}$  linearly decreased the shoot dry weight of tomato plants by 30%. The root dry weight increased at 6000  $\mu\text{mhos/cm}$  but decreased at 10000  $\mu\text{mhos/cm}$ . Height of the first truss was not affected by increasing EC or applying intermittent flow. They measured a decrease of 19% on total and marketable yield when the EC was raised from 2000 to 10000  $\mu\text{mhos/cm}$ , however, this decrease was not statistically significant. The average weight of the marketable yield was not affected by the EC.

A high EC of 10000  $\mu\text{mhos/cm}$  significantly increased the percentage of blossom end rot on fruits, but decreased the percentage of fruit deformity. They also added that their results agreed with those of Winsor (1984) who reported a loss of yield at EC values of 8000 and 10000  $\mu\text{mhos/cm}$ . They cited, however, that Winsor (1984) found that the restriction of early vegetative growth by raising the EC could improve early fruit-set and quality.

Gosselin et al. (1988) conducted a study where tomato plants were grown in nutrient solution with 4 electrical conductivities (2000, 4000, 6000, 8000  $\mu\text{mhos/cm}$ ) in one experiment and 4 NO<sub>3</sub>-N concentrations (70, 140, 210, 280 ppm) in another

experiment to determine the best nutritional conditions for adequate vegetative growth and reproductive development under 2 different lighting levels (125, 250  $\mu\text{mol/s.m}^2$ ). The EC levels were maintained until fruit set of the second cluster and were gradually reduced at a rate of 200  $\mu\text{mhos/cm/day}$  until reaching 2000  $\mu\text{mhos/cm}$ . The EC levels were reached by adding  $\text{NO}_3^-$ , N, K, Ca, and Mg to the basal nutrient solution. Day and night temperatures were maintained at 21 and 16°C respectively.

They concluded that high EC and low nitrogen concentration reduced vegetative growth and favored reproductive development for both light levels. From the first experiment, they observed that the dry matter content increased by about 20 % when the EC was raised from 2000 to 8000  $\mu\text{mhos/cm}$ . Total height decreased with increasing EC. The number of fruits set on the first truss and the number of opened flowers on the second truss, 10 weeks after seeding, increased with increasing EC. The number of days to anthesis decreased by about 4 days when the EC was raised. The authors cited Winsor (1984) reporting that raising the EC to 8000 and 10000  $\mu\text{mhos/cm}$  reduced the number of set fruits.

In a second experiment, the authors reported that percent of dry matter increased when plants were grown with low N concentration (70 and 140 ppm). Also they found that the best yield was obtained at 210 ppm  $\text{NO}_3\text{-N}$  and at a PPFD of 250  $\text{mmol/s.m}^2$ . They also added that their results matched Winsor (1979) which suggested that low nitrogen concentration was more appropriate for plants grown under low PPFD.

Cornish and Nguyen (1989) studied the use of high soil solution electrical conductivity to improve the quality of fresh market tomatoes. Seedlings were transplanted on January 14, 1988 in the first experiment and on December 6, 1988 in the second experiment. They reported that where a high EC (3900  $\mu\text{mhos/cm}$ ) was achieved in the first experiment, there was no effect on fruit firmness or total soluble salts, but titratable acids increased from 7.25 to 8.0 m.e./100ml. In the second experiment, a high EC (>7000  $\mu\text{mhos/cm}$ ) resulted in a small increase in total soluble salts (0.3%) in 1 of 6 harvests and significant increases in titratable acids in 4 harvests. Yield was unaffected in both.

Adams (1991) grew tomato plants in rockwool and compared a salinity of 3000  $\mu\text{mhos/cm}$  with those at 8000 and 12000  $\mu\text{mhos/cm}$  in order to study the effect of increasing the salinity of the nutrient solution with a major nutrient or sodium chloride on yield, quantity and composition of tomatoes grown in rockwool. The seeds were sown in early February and plants were placed on rockwool slabs in mid-March when the buds of the first truss were visible. Nutrient solution treatments were applied at every watering. He concluded that increasing the salinity from 3000 to 8000  $\mu\text{mhos/cm}$  improved both the quality and composition of the fruit. He also concluded that the highest yield were obtained at 3000  $\mu\text{mhos/cm}$  and the lowest at 12000  $\mu\text{mhos/cm}$ . Identical yields were obtained at 8000  $\mu\text{mhos/cm}$  from the two treatments (adding major nutrients in one treatment and NaCl in the other).

Ismail and Burrage (1992) studied the effect of salinity, vapor pressure deficit (VPD) and root temperature on growth and yield of NFT grown tomatoes. Two levels of salinity (2500 and 8500  $\mu\text{mhos/cm}$ ), VPD (0.16 and 0.8 kPa), and root temperature (12 and 22°C) were applied to the plants. The tomato seeds were sown in blocks and transferred to cubes of rockwool in December 1987. The seedlings were transferred to the NFT gullies at the earliest visible first truss bud stage. The plants were grown in recirculating tap water for five days before treatments were applied. The higher salinity level was achieved by adding 1550 ppm NaCl to the basic nutrient solution of 2500  $\mu\text{mhos/cm}$ . The authors concluded that total fruit fresh weight was higher when plants were grown at high VPD and low salinity. The incidence of fruit hollowness was greater at low salinity and high root temperature, but VPD was not a factor affecting the disorder. Analysis of variance did not show a significant interaction between all factors on leaf growth. Leaf area and dry weight were significantly reduced when plants were grown at high salinity, low root temperature and low VPD. They also concluded in this study that the combination of low salinity, high root temperature and high VPD resulted in the highest root dry weight.

CropKing, Inc. (1993) recommended the following EC ranges of a feeding solution at each of the following growth stages: For germination and the early growth stage (starts from the time of growing the seeds until the seeds coat breaks out and the roots come out), maintain an EC between 1800 and 2000  $\mu\text{mhos/cm}$ . For the seedling stage (starts from the time the seeds coat breaks out and the roots come out until

transplanting into the growing media), maintain an EC between 2300 and 2500  $\mu\text{mhos/cm}$ . For vegetative, early fruiting, and mature fruiting stages, maintain an EC between 2300 and 2500  $\mu\text{mhos/cm}$  on sunny days, and between 3500 and 4000  $\mu\text{mhos/cm}$  in the dark winter conditions. The vegetative stage starts from the time of transplanting into the growing media until the first flower opens. The early fruiting stage starts from the time the first flower opens until the first fruit is picked. The mature fruiting stage starts from the time the first fruit is picked until the termination of the crop. They also recommended not having the EC in a perlite bag growing media exceed 300-500  $\mu\text{mhos/cm}$  from the recommended EC for the feeding solution. CropKing growers were advised to move to a different nutrient program after getting blossoms in the second cluster. The new program included higher concentrations of N, K, Mg, and Ca to enhance generative development and reduce the vegetative development.

### **3.2.3 Hydrogen Ion Concentration**

The hydrogen ion concentration (pH) influences the availability of many plant nutrients by influencing the form of the nutrient in a solution. In some studies, researchers attributed poor growth and yield to a low soil pH. Others linked the changes in leaf composition of a hydroponically grown tomato to the pH. Any shift in pH outside the recommended range can have a detrimental effect on plant growth and yield (Siraj-Ali, 1985).

Worley (1972) studied the response of tomatoes to the pH of a coastal plain soil. The tomato plants were transplanted to the treatment plots in early April of 1966, 1967, and 1968. Fruits were harvested at the mature-green stage and graded into marketable, blossom-end rot, fruit rot and other culls. He found that the best marketable yields of tomato were obtained when the soil pH was between 6.5 and 6.9. Yields were reduced when soil pH was below 6.0.

Cooper (1972) studied the influence of container volume, solution concentration, pH, and aeration on dry matter partitioning by tomato plants, cultivar Minibelle, in water culture. In one experiment, the pH was adjusted initially to 6 and then allowed to drift upwards towards 7. In another experiment, pH values of 4, 5, 6, 7, 8 and 9 were initially established and maintained. In another experiment, initial pH values of 5 and 6 were established, but allowed to drift naturally to values of 6.6 and 6.7 respectively. The night temperature was maintained at about 15.5°C, and day temperature at about 21°C with automatic ventilation at 24°C. Cooper concluded in his study that between pH 4 and 7, the dry weights increased by 50%; however, there was little influence of pH on the partitioning of dry matter between cotyledons, roots, stem and leaves. Only for a pH 9 was partitioning affected with relatively more dry matter being found in the roots and cotyledons than in the stem and leaves. He also concluded that the optimal pH of the nutrient solution was near-7.

Wallihan et al. (1977) conducted an experiment to compare tomato growth in pH controlled and uncontrolled cultures with respect to leaf composition and fruit yield. The

authors concluded that tomato plants grown in sand cultures receiving complete nutrient solutions set markedly fewer fruits when solutions were allowed to drift to pH 8 or higher. Leaf analyses showed P deficiency, even though P supply in the sand was apparently adequate.

Islam et al. (1980) conducted an experiment to study the pH for optimum crop growth in six species. One of their objectives was to establish the optimum pH range for certain species to facilitate comparisons with earlier studies and to provide a more adequate basis for generalizations concerning effects of pH on plant growth. They grew tomato and five other species for periods up to six weeks in continuously flowing nutrient solutions at seven constant pH values ranging from 3.3 to 8.5. For the first five days after transplanting the nutrient solution in all flowing culture units was maintained at  $\text{pH } 6.0 \pm 0.1$ . The pH was then adjusted to values of 3.3, 4.0, 4.8, 5.5, 6.5, 7.5 and 8.5.

Tomato was one of the species to show no yield depression at the highest solution pH. They reported that roots of all species at pH 3.3 and some species at pH 4.0 exhibited symptoms of hydrogen ion injury. Also, one of their results was that the concentrations of magnesium and nitrogen in the tops of tomato at these pH values were inadequate for optimal growth. At the end of their experiment, they concluded that all species achieved maximum or near maximum growth in the pH range of 5.5 to 6.5.

CropKing Inc. (1993) suggested that the optimum pH range for growing hydroponic tomatoes should be between 5.2 and 5.5 in the feeding solution and not more than 5.5 to 5.8 in the growing media.



### **3.2.4 Relative Humidity**

Energy savings measures have resulted in increased air humidities in greenhouse atmospheres for most early crops. Increased humidity reduces transpiration from leaves often resulting in less accumulation of nutrients in the xylem (Adams, 1991). Also, a humid atmosphere is an ideal one for the growth and spread of various diseases. Due to that and other significant reasons, several studies were conducted to study the influence of day and night humidity on the growth and yield of tomatoes.

Armstrong and Kirkby (1979) investigated the cation uptake and calcium distribution for tomato plants grown in water culture and air relative humidity (RH) of 50% and 95%. The common environmental conditions in both treatments, were light intensity of  $80 \text{ W/m}^2$ , and a 16 hr light-cycle and 8 hr dark-cycle at temperatures of  $23^\circ\text{C}$  and  $18^\circ\text{C}$  respectively. The plants in the high humidity regime initially grew faster, but after 22 days, dry matter yields were the same for both humidities. Growth of the young leaves was disturbed and the plants showed symptoms of Ca or B deficiency in the high humidity treatment towards the end of the experiment.

Bradfield and Guttridge (1984) investigated the effects of night time humidity and of nutrient concentration on the Ca content of tomato fruits at different stages of growth. They especially studied the Ca concentration on the wall tissue of the distal quarter of the fruit in relation to the incidence of blossom-end rot. The day and night temperatures were kept at  $22 \pm 1.5^\circ\text{C}$ , and  $18 \pm 1.5^\circ\text{C}$  respectively with a 16 hr day light. In one of the experiments, they found that the Ca intake into tomato fruits was greater when nights

were humid (Vapor pressure deficit (VPD) = 260 +/- 110 Pa equivalent to RH=87%) rather than dry (VPD 760 +/- 110 Pa, equivalent to RH=64%), and when nutrient solutions were dilute rather than concentrated. The VPD on dry days was 1000 +/- 170 Pa which is equivalent to 61% RH. They observed that the concentration of Ca in the wall tissue of the distal segment of fruits damaged by blossom-end-rot was 0.03% of dry matter, but was 2 to 3 fold greater in the most favorable conditions of humidity and solution concentration. The authors also added that their results agreed with the conclusion of Armstrong and Kirkby (1979) that maintaining high levels of humidity during the day restricted calcium uptake by the plant. The authors concluded that adequate transport of calcium into the fruit is best achieved by maintaining high relatively humid conditions at night, and by avoiding excessively concentrated solutions at the roots during the early growth of the first and second truss.

Banuelos et al. (1985) studied the effect of air RH on the appearance of blossom end rot in the tomato fruits. Tomato was grown in the greenhouse under normal conditions. The approximate daylength was 12 hr during the summer. The temperature was 19°C and the RH was 55% +/- 5%. On day 51, after pollination of flowers in the first truss, plants were transferred to growth chambers with either 95% or 55% RH. Light and dark temperatures were 18 and 15°C, respectively, with a 16 hr light and 8 hr dark cycle.

Blossom-end rot symptoms developed at the distal-end on the young green fruit within 15-16 days at 95% RH. They also observed through the plant tissues from plants

grown at high RH that they had lower Ca concentrations than comparative tissues of the low RH plants and exhibited increased growth compared to the low RH regime plants.

Gislerod et al. (1987) studied the effect of RH on nutrient uptake of nine different greenhouse species for 24 to 100 days, at 55-60, 70-75, and 90-95% RH corresponding to 8.5-9.6, 5.3-6.4, and 1.1-2.1 mbar water VPD. The air temperature was kept at  $18.5 \pm 0.5^\circ\text{C}$ . For the *Lycopersicon esculentum*, they observed a 44% decrease in the transpiration rate by increasing the RH from the lowest to the highest level. Also, they noticed a significant decrease for the K and Ca in the plant leaves of *Lycopersicon* with increased RH. The content of N and K in the growth medium at the end of the experiment was lowest when the plants had been growing at high RH. The authors mentioned that Adams and Ho (1985) showed that a constantly high RH decreased the Ca content in the young leaves of tomato. They also added that with a constant RH during the day and night, significant differences in the content of K, Ca, and Mg were found in *Lycopersicon*.

Holder and Cockshull (1990) investigated the effect of four discrete humidity treatments (0.1, 0.2, 0.4, and 0.8 kPa VPD) maintained continuously for 28 days from January 15 to February 12, 1987 on the growth and yield of a long-season tomato crop. The VPDs achieved over the 28 day period were 0.15, 0.25, 0.43, and 0.65 kPa which is equivalent to RHs of 93, 88, 79, and 69% respectively. Two levels of electrical conductivities (5000 and 7000  $\mu\text{mhos/cm}$ ) were maintained from the time that contact was established between the propagation cube and the rockwool slab until two weeks

before fruit were picked. Conductivity levels were then lowered gradually to 3000 and 5000  $\mu\text{mhos/cm}$  respectively.

They reported that the rate of plant development was unaffected by humidity. However, significant reductions in leaf area at high humidities (88 and 93%) were associated with low calcium concentrations in the leaf laminae and other calcium deficiency symptoms in the plant. There were no calcium deficiency symptoms in the fruit. They observed that trusses associated with the smaller leaves produced smaller fruit and lower yields compared with the low humidity treatments. They also noticed that fruit picked before and after these trusses were unaffected by the humidity treatments. They added that high humidity also reduced fruit quality. One of the things that they concluded from their study was that the cost of reducing humidity to a VPD greater than 0.3 kPa (equivalent to 86% RH) was likely to exceed any economical gain, because the yield response to lower humidities was very small.

Bakker (1990) studied the effects of different day and night humidity levels on two spring crops and one autumn crop of tomato. A high or low humidity by day was combined with either a high or low humidity by night. In experiment one, the VPD varied from 0.35 to 0.45 kPa by day, from 0.21 to 0.52 kPa by night and the 24 hr mean varied from 0.23 to 0.47 kPa. In experiment two, night-time humidity was similar to that in experiment one, but humidity by day was lower. VPD by day varied from 0.62 to 0.72 kPa, by night from 0.25 to 0.57 kPa and the 24 hr mean varied from 0.38 to 0.60 kPa. In experiment three humidity was generally lower than in experiments one and two. VPD

by day varied from 0.51 to 1.01 kPa, from 0.27 to 0.71 by night and the 24 hr mean from 0.35 to 0.8 kPa. The temperature differences between the treatments were restricted to less than 0.7 °C.

They noticed that calcium deficiency and concomitant leaf area reduction was most severe under continuously high humidity. Stomatal conductance was significantly increased by high humidity. They found that early yield was higher at high humidity by day, but final yield was reduced by either a high humidity by day or night. Also, in this study the authors noted that the mean fruit weight and keeping quality were reduced under high humidity.

Regarding the vegetative growth and development in the high day/high night treatment (0.35/0.21 kPa; equivalent to 87/89 % RH) of experiment one, the percentage of distorted trusses was significantly higher than in the other treatments. Calcium deficiency in leaves was higher in the continuous high humidity than in the other treatments in experiment one and three. The high day/high night humidity treatment of 79/87% RH also significantly reduced the leaf area between trusses four and seven and total leaf area until truss eight in experiment three.

Regarding the fruit production and quality, they found that the mean fruit weight of the final yield was significantly lower at the high day/high night humidity than that of the other treatments. They finally concluded that long term humidity was detrimental to yield and keeping quality. They added that positive yield responses were most pronounced at very low VPD levels. They advised that humidity control with tomato

should concentrate on avoiding long-term high humidity in order to optimize fruit production and quality.

Adams (1991) continued a study that was designed to study the effects of high humidity during the day or at night on the growth, yield and quality of early tomatoes. In that study tomato plants were grown at four humidities (VPD of 0.15, 0.25, 0.43, and 0.65 kPa; corresponding to RH of 93, 88, 79, and 69% respectively) that were maintained continuously for four weeks.

Adams observed that a high humidity (93%) at night reduced the Ca, Mg, P, and K contents of all portions of the leaf lamina while a high humidity during the day reduced only the Ca and K contents. They also reported that N content was not affected by humidity. The Ca and K contents of the petioles were reduced by a high humidity during both day and night. The changes in the Ca, Mg, and K contents of the tissue in response to high humidity were greater in the terminal leaflet than in the basal leaflet or in the rest of the lamina, suggesting that the terminal leaflet was suitable for monitoring the nutrient status of the crop. Yellowing of the terminal leaflet at high humidity was associated with deficiencies of both Ca and K rather than with Ca only. They also added that their data confirmed that continuously high humidity caused the most severe symptoms and that high humidity either during the day or at night had a similar effect. They mentioned that these results supported previous findings for young tomato plants that high humidities decreased the percentage of Ca (Armstrong and Kirkby, 1979), as well as K in the leaves (Banuelos et al., 1985; Gislserod et al., 1987).

Adams and Holder (1992) studied the response of early tomatoes to salinity levels of Ca applied in combination with a range of humidities. The two levels of salinity tested were 5000 and 7000  $\mu\text{mhos/cm}$  and the two levels of Ca were 150 and 300  $\text{mg l}^{-1}$  in the nutrient solution. The humidity treatments, defined as VPD were, 0.15, 0.25, 0.43 and 0.65 kPa corresponding to RH of 93, 88, 79, and 69 % respectively, were held constant for day and night in experiment A, and high (0.21 kPa) or low (0.47-0.55 kPa) during the day in combination with high (0.16 kPa) or low (0.45-0.50 kPa) at night in experiment B. They used the accumulation of the dry matter by the leaves to assess the effects of the different treatments on plant growth. They found that high humidity reduced the dry weight of the leaves, as did the higher salinity. Also, they noticed that the Ca level (%) and the total amount of Ca (mg) accumulated by the leaves always decreased at high humidity with the response being greater at night than during the day. Accumulation of Ca by the fruit was markedly reduced by low humidity during the day. High humidity during the day promoted Ca movement into the young fruit, irrespective of the humidity at night.

Comparing their results with the results of the previous studies, the authors mentioned that dry matter accumulation by the leaves always decreased with high humidity in accordance with the decrease in leaf area found by Holder and Cockshull (1990) and Bakker (1990). They added that Armstrong and Kirkby (1979) showed that marked reductions in the dry weight of the leaves occurred after 22 days at 95% RH compared with those grown at 50% RH despite the initial increase in whole plant height

at 95% RH. This result suggested an initial stimulation of growth consistent with the work of Acock et al. (1976). They added that this may explain the increase in the dry weight of the young and old leaves grown for 15-16 days at 95% RH as compared with those at 55% RH reported by Banuelos et al. (1985).

CropKing Inc. (1993) recommended to keep RH between 70 and 80 % in the area around the growing media and 100% around the seed during the germination and early growth stage. For the vegetative, early fruiting, and mature fruiting stages, they recommended to keep RH below 90% and between 60 and 80% when pollinating the flowers.

### **3.2.5 Air Temperature**

Numerous researches have studied the effect of air temperature (AT) variation on the quality of hydroponically grown tomatoes. The growth, flowering, and fruit sets were all found to be highly affected by the AT inside the greenhouse. Studies have also been done on the effect on growth and yield of tomatoes by fluctuating the day and night air temperature.

Calvert (1964) studied the effect of temperature on the growth of tomato plants up to six weeks old grown during a number of winter periods (October to March) under natural light conditions. He also investigated the agreement that existed among other authors as to the range of temperatures (15.5 - 21.1°C by day and 10 - 15.5°C by night) most likely to produce satisfactory growth.



The plants were grown with the same day-temperature and at three night temperatures: (a) 2.22°C lower than the day; (b) equal with the day; and (c) 2.22°C higher than the day. The day temperatures were 15.5, 17.8 and 20°C respectively for the three experiments.

Calvert found that growth rates were lowest when night temperature was lower than the day. The growth rate was generally higher when the night temperature was high. With higher day temperatures, however, this was not the case. There was little evidence that the temperature inducing maximum growth was related either to the light conditions or to the age of the plant. The response to night temperature was small by comparison with response to that of the day. The highest growth rates were achieved when the night temperature was not lower than 17.8°C and the day temperature was not lower than 20°C.

Cooper and Cooke (1964) studied the effects of shading and unshading glasshouses on fruit-ripening disorders and crop yield maintained at both high (26.5°C) and low day temperatures (18.3°C). Two varieties of tomatoes were grown at two levels of watering (1.4 and 1.07 pints per plant per day in 1959; 1.62 and 1.58 pints per plant per day in 1960).

Eventhough the authors mentioned that the layout of the experiment had severe statistical drawbacks, the interaction between the shading and the temperature appeared significant. Shading the glasshouse reduced the proportion of non-uniformly colored fruit at the high temperature. At the low temperature, shading reduced the proportion of non-uniformly colored fruit in 1960, but there was no effect in 1959. Shading the

glasshouses reduced yield in both years. The house at the low day temperature yielded a 30% greater weight of crop than the warmer house.

Abdalla and Verkerk (1968) compared the effects of high temperatures of 35°C day and 25°C night with normal temperature of 22°C day and 18°C night on the growth, flowering and fruit set of the tomato. The seeds were sown in flats in a glasshouse kept at approximately 22°C day and 18°C night temperature during the period March till May. When the seedlings were four weeks old, they were transplanted into 12 inch pots for treatments. The experiment showed that under the first temperature conditions, stem growth was twice as fast, giving thin stems and many trusses with weak flowers. In many cases, styles were as long or even longer than the stamen tube and flower shedding was remarkably high. In most cases, fruits developed only from the first and second flowers of the truss. Also the fruits formed under high temperatures ranged between 1 and 3 per truss, while under normal temperature, fruit yield ranged between 3 and 6 fruits per truss. Pollen germination was best at 27°C, but tube growth of pollen from high temperature was slower than normal. Pollen counts on the stigma showed very limited amounts of pollen at high temperatures compared to the control.

Abdelhafeez and Verkerk (1969) studied the effect of temperature and water-regime on the emergence and yield of tomatoes. Five days after sowing, seedling emergence was recorded daily between April 21 and May 7; when 8 plants each from 24 and 18°C were analyzed. They found that seeds at 24°C had an earlier and higher seedling emergence than those at 18°C. Seeds at 9°C failed to emerge even after 42 days,

irrespective of the water regime. When the pots were transferred to a glasshouse at 35 °C by day and 18°C by night, however, the seedlings appeared.

They compared 24, 18, and 9°C together with wet, medium, and dry soil moisture conditions. The wet pots were kept at constant weight of 10% depletion from field-capacity, while the medium pots were kept at a 20% depletion from field capacity, and the dry soil moisture pots were only brought to field-capacity at the beginning of the experiment and never rewetted. The higher temperature receiving the wettest treatment showed the earliest and best emergence, followed by those at 18°C. The authors suggested that this may be due to the fact that with decreasing water content the seeds were subjected to an increasing water-stress. The number of leaves below the first truss was about 2 more after growing the young plants at 24°C than at 18°C.

A crop yield experiment showed that the plant lengths were a little larger at 20°C than at 35°C. This may have been due to the light intensity differences since the glasshouse plants at 20°C received only 80% of incoming radiation as the outdoor plants at 35°C. As to the truss capacities and earliness, the lower temperature treatment showed the higher truss capacity and the higher temperature showed the earlier fruit set and the higher numbers of fruits larger than 30 mm. The fruit weight was the same for both temperatures. Plants at 35°C had higher numbers of flowers shedding than those at 20°C receiving similar watering, but flower shedding was highly significant only in the dry treatments.

Abdelhafeez et al. (1971) studied the effect of soil and air temperatures on growth, development and water use of tomatoes in two series of trials. In one trial, tomato plants were grown in a glasshouse without air temperature control at soil temperatures ranging from 14 to 29°C. In the other trial, tomato plants were grown in phytotron glasshouses at constant air temperatures of 17°C, 21, and 25°C and at soil temperatures ranging from 12 to 30°C. A low air temperature (17°C) resulted in a late, but relatively rich flowering. After three weeks, there were no open flowers in the glasshouse and in the phytotron compartment with an air temperature of 17°C. At air temperatures of 21 and 25°C, the percentage of open flowers in the first truss was 15 and 50, respectively.

Abdelhafeez et al. also found that during the last three weeks, the total dry-weight increase was slightly affected by the air temperature, being relatively low at 17°C. They suggested that because of the increased earliness at higher air temperatures, a greater part of the dry matter produced was used for fruit development, resulting in a significantly reduced vegetative growth at the higher air temperatures. Consequently, plants at 21 and 25°C showed relatively thin stems and the yielding capacity was reduced. They added that constant air temperatures of 21°C or higher forced the tomato plants into such a quick development that there was an unfavorable balance between vegetative and generative growth. A similar effect of air temperature on earliness and fruiting capacity was reported by Abdelhafeez and Verkerk (1969). The authors also reported that, at 22°C, the plants apparently could maintain a favorable water balance during the day without stomatal closure.

Khayat et al. (1985) studied the effect of various night-temperature regimes on the vegetative growth and fruit production of tomato cultivars, Moneymaker and Cherry. A night temperature of 18 °C was maintained during the germination period. Following germination, the plants were then transferred to 3 greenhouse compartments with different night-temperature regimes of 18 +/- 1°C, 12 +/-1°C, and 18 and 12°C repeated every 2 hr. The minimum and maximum day temperatures of 18 and 30°C were maintained. They concluded that the temperature optima of the tomato plants varied in proportion to the variables observed. They cited Picker et al. (1985) as recommending the maintenance of higher temperatures during the vegetative growth of the seedling before the first inflorescence is formed, with a further decrease in the night temperature.

Hurd and Graves (1985) studied some effects of air and root temperatures on the yield and quality of glasshouse tomatoes. Tomato seeds were sown in NFT in November where air and root temperature variables were applied at the beginning of flowering. Air temperatures were only reduced at night when 65-70% of the 24 hr fuel consumption occurred. At about the fifth leaf stage when flower buds were just visible, temperatures were held at 18/15°C day/night through 50% flowering of the first truss (inflorescence) after which the treatments were started. The ventilating temperature was 23°C, rather than the normal 26°C, to reduce overheating the nutrient solutions. The atmosphere was enriched with CO<sub>2</sub> during the hours of daylight. The roots were either unheated or kept at 17, 22 or 27°C throughout the experiment. The authors in this experiment concluded that when economic effects of the various treatments were compared, the highest air and

root temperature were shown to be the highest yield and the most profitable, even allowing for the fuel cost. This conclusion was at variance with other work, however, which indicated that lower air temperatures could be profitable.

De Koning (1988) examined the response of glasshouse grown tomatoes, cultivar Counter, to day/night temperature regimes in two consecutive years. In both years, three day/night temperature regimes, with the same average 24-hour temperature, were applied in duplicate, i.e. high/low, equal, and low/high. In experiment one, the high/low, equal and low/high average temperatures achieved were 20.8/16.3°C, 19.6°C during the day and 17.5°C at night, and 18.3/18.4°C, respectively. The 24-hour temperature was kept around 17.7°C. In experiment two, the high/low, equal, and low/high temperatures were 21.3/16.9°C, 20.6°C during the day and 18.0°C at night, and 19.8/18.6 °C, respectively. The 24-hour temperature was kept around 18.7°C. Differences in temperature were maintained from three days after planting (December 4, 1984 and February 3, 1986) until May 13, 1985 and May 1, 1986, respectively.

Plant development (increase in number of trusses) was not affected by the various temperature regimes. Growth in stem length was strongly reduced by a lower day temperature. The main stem and the truss stems became firmer and therefore the latter were less susceptible to distortion. The author mentioned that Calvert in 1964 suggested that plant height depended only on the day temperature and that higher night temperature did not give longer plants.

In the first experiment, the crop at the low day temperature was damaged by leaf scorch, most likely caused by low transpiration. Consequently, early yield was lower for this treatment. In the second experiment, no leaf scorch occurred and no significant differences in early yield were found.

Final yield and average fruit weight, up to July 1, were higher at the higher night temperature in both experiments. The authors mentioned that obtaining equal or even higher yields in a reversed temperature regime did not agree with several other researchers who found that growth of tomato was best in a high day temperature regime. These results, however, were obtained with young plants that seemed to achieve a fast increase of light interception and maximum growth at high day/low night temperature regimes. It was noted that a night temperature higher than or equal to the day temperature reduced the risk of water vapor condensing on plant leaves early in the morning, and thus reduced the risk of infection with *Botrytis* and other fungi.

Shelf life of the fruit and the internal quality was not influenced by the temperature regime. Thus, the height of a tomato plant can be manipulated by the difference between day and night temperature, while development and early yield depended greatly on the average 24-hour temperature.

De Koning (1992) concluded that the development rate of tomato depended on the average temperature only, while internode length was affected strongly by the day/night temperature regime, i.e. short internodes at low day/night temperature difference. In an earlier study De Koning (1987) found that the flowering rate equaled about 1 truss per

week and was enhanced by 24 hr temperature (for each treatment day and night temperature were the same) with 0.05 truss per week per °C for temperatures of 17, 19, 21, and 23°C.

Dane et al. (1991) studied the effect of high temperature on fruit set, pollen fertility, and combining ability of selected tomato genotypes. Six-week-old plants were transplanted each year in mid-June. The daily maximum temperature ranged from 29 to 36°C and the daily minimum from 17 to 24°C in July and August, 1985. They concluded that a decrease in pollen fertility was a limiting factor during prolonged periods of high temperature heat stress. Several small-fruited genotypes still maintained a high level of pollen fertility under heat stress and some genotypes transferred a small degree of heat tolerance to their offspring.

Abu Hadid (1991) recommended that the temperature during the seedling phase should range from 18 to 20 C. During vegetative phase, temperature should range from 12 to 15°C at night and 18 to 22°C during the day. During the early fruiting and the mature fruiting phases, the night temperature should range from 14 to 16°C and the day temperature from 22 to 28°C.

CropKing, Inc. (1993) recommended that for rapid germination, the optimum temperature should range from 25 to 26.1°C for the first 96 hrs (four days) after seeding. During the early seedling growth (day four to two weeks after seeding), the optimum temperature should be 23.3°C during the day and 20°C at night. From the end of the second week until transplanting into the growing media, the temperature should range



from 21.7 to 22.8°C on the cloudy days, 25 to 25.6°C on sunny days, and 18.3 to 20°C at night with a minimum of 17.2°C at night. During vegetative, early fruiting, and mature fruiting stages, air temperature should range from 20 to 21.1°C on cloudy days, 22.8 to 25.6°C on sunny days and 17.2°C minimum at night.

### **3.3 Greenhouse Crop Growth Modeling**

This section describes the key studies done on the modeling in greenhouses, as well as the different types of models developed. Challa (1981) classified the models used for greenhouse climate-research into the two categories of empirical and mechanistic. Empirical models use statistics to describe the relationship between environment, crop response and energy costs in some empirically obtained equations (black-box models). Mechanistic models describe a system on the basis of physical and physiological theories (explanatory models).

Kindejan (1980) developed a model to predict the time evolution of the conditions in a certain greenhouse as a function of the climatological conditions existing at a hypothetical location. The external climatological conditions used in the preliminary simulations were: wind speed constant, relative humidity constant, solar radiation zero during the night and parabolic during the day with the maximum at noon time, and temperature a harmonic function characterized by mean value, amplitude of oscillation, and delay.

As an attempt to analyze the influence of the mean external temperature, amplitude of oscillation of the external temperature and maximum radiation respectively,

the author observed that the humidity during the night increased with increasing external temperature, with decreasing amplitude of oscillation, and with decreasing solar radiation.

Cooper and Fuller (1983) described a computer-based method of modeling the transient performance of greenhouses. They developed a method to assist in the design of low energy protected cropping structures to be used in the hot, arid inland climates of Australia. They considered the greenhouse to be composed of a number of separate, but interactive components. These were the cover, floor, growing medium, air space and crop.

The authors presented details of the mathematical models of each component and listed the assumptions used with each.

Bogmann (1983) developed a bio-economic simulation model for planning and control in greenhouse production. It took into account the biological and engineering aspects of the production as well as the economic ones like: the variety of growing techniques, labor methods and the technical equipment. The core of the simulation was formed of four submodels: the calculation of indoor climate, heating energy, growth and of man and machine hours.

McAvoy (1989) tested the accuracy of a computer planning model for the management of a single truss tomato (*Lycopersicon esculentum* Mill) production system. The model was used to generate a production schedule for 24 successive crops during a 15-month study. The time, in days, required for an emerging seedling to reach anthesis

and the total fresh weight yield were predicted for each of the 24 crops by the planning model.

Correlation analysis, used to compare the expected crop response (i.e., data generated by the planning model) to the actual response, indicated that both the number of days from emergence to anthesis and fresh fruit yield were accurately forecast,  $r^2 = 0.76$  and  $0.83$ , respectively. More important, the cropping schedule that was generated by the planning model successfully predicted a continuous harvest of tomatoes from sequential crops.

Avissar and Mahrer (1982) designed a numerical, one-dimensional model to simulate the diurnal changes of the greenhouse environment. The model consisted of: a soil layer, a vegetation layer, an air layer and a cover. The thermal radiative, sensible, latent and conductive heat fluxes were modeled in each layer in terms of its unknown temperature and vapor pressure. Numerical experiments were conducted to test the sensitivity of the model to some variables. The results indicated the necessity to properly initialize the model and to determine an accurate inside air transfer coefficient of sensible and latent heat. The authors performed an observational study in order to test the ability of the model to properly describe the greenhouse microclimate. Good agreement was obtained between predicted and observed temperatures and humidities.

Bruggink et al. (1988) presented a dynamic model which predicted water potential and water uptake rate of greenhouse tomato plants using transpiration rate as input. The model assumed that water uptake was the resultant of water potential and hydraulic

resistance, and that water potential was linearly related to water content of the plant. A comparison of the measured and predicted values showed a reasonable correspondence.

Fynn et al. (1989) developed a decision model for nutrient management in controlled environment using the concepts of decision analysis and expert systems. The decision model decided upon the selection and application of nutrient mixtures to a cucumber crop based upon a calculated future solar irradiance levels within the coming day. Four expert system rulebases were used to feed data into the decision tree and the rules were derived using telephone conversations, intensive discussions, videotape recordings, with an expert production consultant, data analysis, and reported knowledge in the literature.

Seyd and Feller (1989) designed an information system called the vegetable production monitoring and control system (VPMCS). The VPMCS was designed for planning, managing and monitoring the production of vegetables on specified minimum farming units such as fields or parts of them. Basic data about specific fields, soil and plant related activities and checks carried out and the material, equipment and personnel to be used were stored in data banks. With a view to selecting suitable varieties, applying nitrogen fertilizer, making yield forecasts or providing other types of information of relevance from an agricultural, crop production and technological perspective, those data banks and the management programs that go with them were linked with elements of an expert system for the management of crops.

Heuvelink and Marcelis (1989) described a model to simulate dynamically the distribution of dry matter between leaves, stem, roots and individual cucumber fruits or tomato clusters of fruits. They found that potential dry weight and time from flowering until harvest of tomato clusters of fruits decreased with increasing temperature (17, 21, or 25°C). However, the relation between sink strength (potential growth rate) and developmental stage of a cluster (time after flowering /time from flowering until harvest) was almost independent of temperature. The simulated dry matter distribution between tomato leaves, stem, and individual clusters of fruits corresponded reasonably well to the measured data from a glasshouse experiment.

Hildman (1989) developed a strategy for the optimization of air temperature in greenhouses cucumbers based on a yield formation model. The optimum temperature was calculated for a fixed CO<sub>2</sub> concentration of 800 ppm without ventilation and for a concentration of 500 ppm when the greenhouse was ventilated. Optimal temperature was fixed for periods of nine days.

One result obtained with the optimization strategy was that the 9 day mean temperature (24 hr means) should be between 17 and 24°C. The 9 day mean CO<sub>2</sub> concentration during the day in the period without venting was between 600 and 900 ppm, and in the period with ventilation was between 400 and 700 ppm. During the production experiment that started February 10 and lasted through September 5, they reached a yield of 33.8 kg/m<sup>2</sup> and an output of 198 Mark/m<sup>2</sup>.

Beer and Ansonage (1989) presented a system of computer-aided fertilizer recommendations (DS 87) that facilitated decision-making in the use of N, P, K, Mg, Ca and micro-nutrients (B, CU, Mn, Mo, Zn) and organic manures for 33 field vegetables. Recommendations were given on the level and splitting of fertilizer doses, along with hints on the appropriate date and method of fertilization and the form of fertilizer to be used.

Gohler (1989) studied the significance of hydroponic systems in obtaining high and stable yields as well as for the economical use of water and nutrients and for reduced environmental stress. The authors compared three different control principles with tomatoes. They concluded that the third control principle seemed to be the best one allowing the surplus nutrient solution to be reduced by 5 to 10%. They also recommended that the long term orientation must be directed to closed hydroponic systems.

Biemond (1989) described in detail a growth model for heated glasshouse tomatoes. Both development and real growth were distinguished for both crop and fruit using a mechanistic approach. He showed some results of the growth model as part of a bio-economical model. Of the different physiological processes, the rate of photosynthesis showed the largest influence on productivity. Other regarded aspects were: rate of flowering and maturity, tomato type, intercropping and planting date.

Nederhoff (1989) validated a dynamic, explanatory simulation model for greenhouse crop photosynthesis with two series of measurements in an experimental

greenhouse with cucumber. The employed method was based on calculation and measurement of carbon dioxide balance of the greenhouse air. The simulated rates of photosynthesis generally showed a strong similarity with the measured photosynthesis rates.

Jones (1990) linked two separately developed simulation models and used them to evaluate different environmental control strategies in a Florida tomato production greenhouse. POLY-2 was a model of a double poly, Quonset-style greenhouse. It was a dynamic model that simulated environmental control equipment actions. TOMGRO was a dynamic crop model that simulated growth, development, quantity and timing of yield of tomatoes. Both models were based on independent empirical data sets used for calibration and validation. The two models were linked by incorporating Poly-2 into TOMGRO as a subroutine. Historical weather data for Tallahassee, Florida and Raleigh, North Carolina were used in turn by TOMGRO to simulate development and growth of the tomato crop. During simulation runs POLY-2, kept track of heating fuel requirements and TOMGRO kept track of tomato yield. Simulations over a range of setpoints showed that the optimal setpoint depended directly on the price of fuel, the value of the tomatoes, and location.

Yang et al. (1990) developed a theoretical model of greenhouse microclimate for describing heat and mass transport processes in a greenhouse row-crop stand, including radiation transfer, energy balance, transpiration and CO<sub>2</sub> exchange. The general theoretical considerations were assembled into a dynamic simulator by applying energy

and mass balances simultaneously over differential strata of plant leaves and greenhouse air. Outputs of the simulator included both diurnal courses and vertical profiles of leaf temperature, air temperature, humidity and  $\text{CO}_2$  concentration in addition to energy and mass exchange.

Jones (1991) developed a physiological model of tomato crop development and yield. A series of differential equations represented the changes in numbers and weights of leaves, fruit, and stem segments in the areas of leaves as new organs were initiated, aged, and senesced or were picked. The model used a source sink approach for partitioning carbohydrate into growth of different organs. They conducted an experiment in six outdoor, controlled environment, growth chambers to quantify the effects of temperature,  $\text{CO}_2$ , and light on tomato growth processes for calibrating the model. The model accurately described the differences in growth and yield of tomatoes that were observed in the experiment. They concluded that the current model can be used to study the possible effects of different environmental control strategies over practical ranges of  $\text{CO}_2$ , light, and temperature. With additional testing, the model could be used to help determine strategic and tactical decisions concerning greenhouse environment control over practical ranges of  $\text{CO}_2$  and temperature.

Seginer (1993) mentioned that greenhouse environmental controllers were required to maintain as accurately as possible pre-set setpoints. However, a new generation of control schemes were emerging where the setpoints themselves were continuously changed according to internal rules, which utilized some kind of a crop



model. The setpoints were selected to optimize the growth of the crop in view of a certain performance criterion, such as net income. The author divided the various control schemes which were described in the literature into certain classes, according to whether they use explicit crop models and or require information about the future for each decision.

As a support system for investment strategies, Rijdsijk and Houter (1993) developed a computer model for energy consumption, CO<sub>2</sub> consumption and crop production (ECP-model). The main factors predicted were gas consumption and crop production for tomato, cucumber or sweet pepper. Cumulative gas consumption over a year was simulated by the ECP-model with an accuracy greater than 90% and cumulative crop production with an accuracy greater than 95%.

It is clear that extensive research has been done on modeling in greenhouses. However, there is still a great need for a decision model that can aid hydroponic tomato growers in producing a high-quality crop. This model should integrate the knowledge of the experts in terms of both the key decisions and optimum ranges required to produce the best quality crop, and the actions needed to correct the unacceptable results of the key tests. Most importantly, this model should integrate the expertise in terms of prioritizing the unacceptable results.

## **CHAPTER IV**

### **DEVELOPMENT OF A DECISION MODEL**

#### **4.1 Introduction**

This chapter consists of three sections. The first section explains the Hydroponic Tomato Production Decision Model (HYTODMOD) that was developed as a main program with subroutines. In the second section, the suggested prioritization scheme is presented. In the third section, the graphical representation of the prioritization scheme by the decision tree is presented.

#### **4.2 Decision Model**

The general objective of this research was to develop an integrated decision model for a hydroponic tomato grower that would prioritize the necessary actions based on the probability of producing high yield, high quality fruit. The decision model was designed to accomplish this general objective by achieving the following **specific objectives**:

- 1) Identify the necessary key tests to produce high yield, high quality fruit.
- 2) Identify the acceptable optimum ranges for the results of each test.
- 3) Identify the appropriate action required based on the results of the test.
- 4) Prioritize the necessary actions using the utility theory of decision analysis.

The decision model consists of a main program and 28 subroutines. A flow chart of the decision model is shown in Figure 4.1.

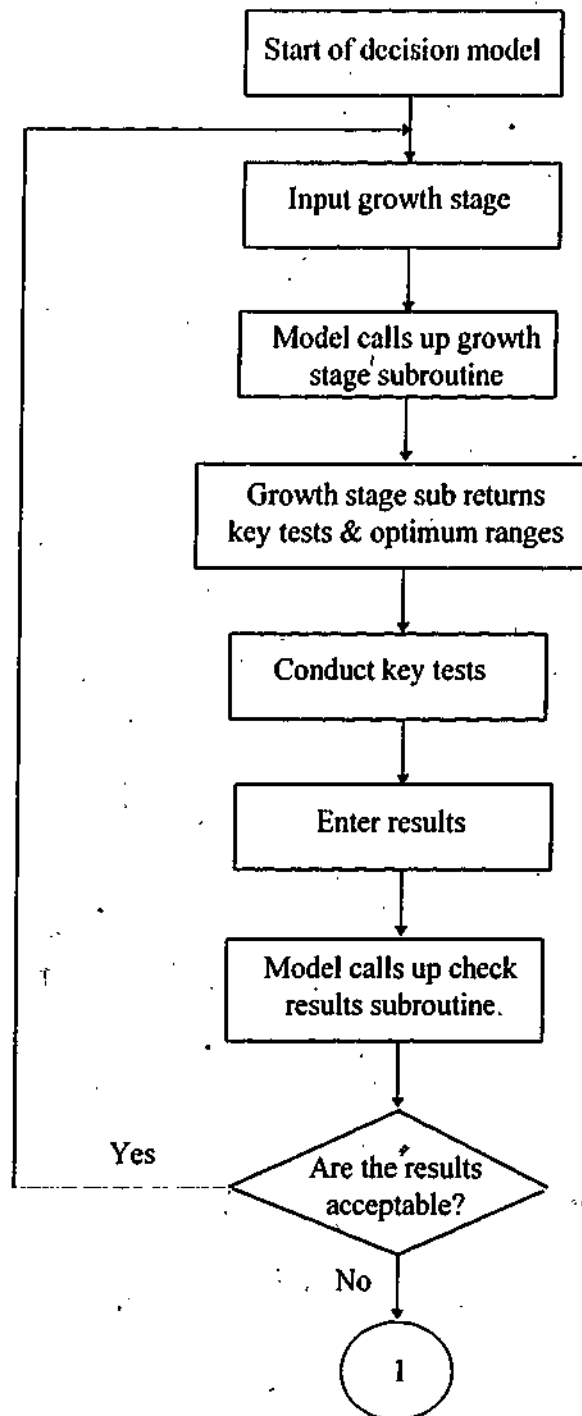


Figure 4.1 Flow chart of the Decision Model

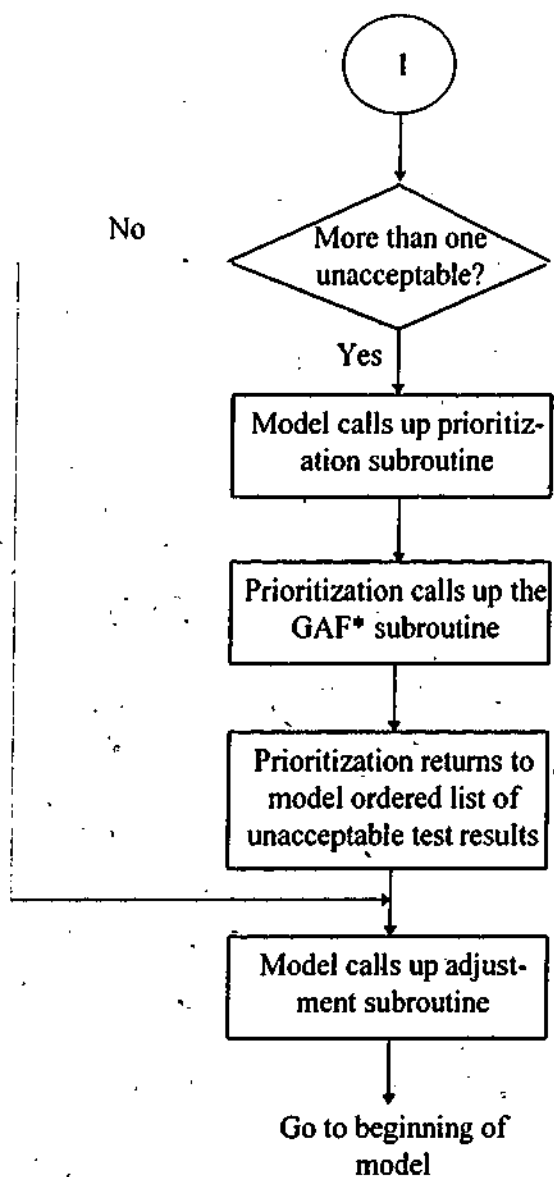


Figure 4.1 (continued) Flow chart of the decision model

\*GAF: Growth Activity Function.

#### **4.2.1. The Main Program**

The main program served as a communication link among all the subroutines.

The decision model initially asked the user about the growth stage, then called up the corresponding GROWTHSTAGE SUBROUTINE.

#### **4.2.2 The Growth Stage Subroutines**

A hydroponic tomato production process was divided into five stages as defined by (CropKing, Inc. 1993):

- 1) Germination and early growth stage: starts from the time of sowing the seeds until the seeds coat breaks and the roots emerge.
- 2) Seedling stage: starts from the time the seeds coat breaks and the roots emerge until they are transplanted into the growing media.
- 3) Vegetative stage: starts from the time the seeds are transplanted into the growing media until the first flower opens.
- 4) Early fruiting stage: starts from the time the first flower opens until the first fruit is picked.
- 5) Mature fruiting stage: starts from the time the first fruit is picked until the termination of the crop.

The above five growth stages were programmed into the decision model in seven growth stage subroutines. One is for the germination and early growth stage, three are for

the seedling stage (one for cloudy conditions, one for sunny conditions, and one for night weather conditions), and the other three combine the vegetative, early fruiting, and mature fruiting stages together with cloudy, sunny, and night weather. Each of these seven subroutines identified for the user the key tests for each growth stage and their optimum ranges to produce the best quality crop.

#### **4.2.3. The Checkresults Subroutine**

After carrying out the appropriate growth stage subroutine, the decision model asked the user to enter the current values of the key tests inside the greenhouse. Next, the model called up the Checkresults Subroutine. This subroutine was used to compare the values entered by the user with the optimum ranges of the key tests identified in the growthstage subroutine.

The Checkresults subroutine returned to the main program one of three outcomes: i) all variables are acceptable, or ii) one variable is unacceptable, or iii) more than one variable is unacceptable. If all variables were acceptable, the main program started from the beginning. If there was one unacceptable variable, the main program next called up a corresponding Adjustment Subroutine (explained below) and started from the beginning. If more than one variable was unacceptable, the main program called next a Prioritization Subroutine, which in turn called the appropriate Growth Activity Function (GAF) subroutine (explained below). The Prioritization Subroutine returned to the main

program an ordered list of the unacceptable tests. Finally, the main program called up the Adjustment Subroutine, and then started from the beginning.

#### **4.2.4 The Adjustment Subroutines**

If the Checkresults subroutine detected any unacceptable variables, the main program called up a corresponding Adjustment Subroutine. This subroutine suggested for the user the actions needed to correct unacceptable variable. There were five adjustment subroutines: one for pH, one for EC, one for air temperature, one for root temperature, and one for relative humidity.

#### **4.3 Applying the Utility Theory to the Prioritization Scheme**

When running the model, it was assumed that a grower would be dealing with a situation in which more than one variable needed to be adjusted. It was crucial, therefore, that the grower could determine which variable was most critical in order to ensure the quickest, positive results. The prioritization subroutine in the HYTODMOD model was designed to assist the grower significantly in prioritizing the variables for adjustment. The methodology of the prioritization scheme was carried out using the utility theory of decision analysis.

A set of axioms needed to be satisfied in order to apply the utility theory to the prioritization scheme. Van Neumann and Morgenstern (1947) established a set of axioms for their theory of expected utility. These axioms have been refined by a number of

researchers, so that the essential ideas of Von Neumann and Morgenstern have been condensed into three basic axioms. These axioms specify the conditions of an individual's preference over pairs of risky prospects (Pratt et al, 1964, Anderson et al, 1977, and Bell, and Farquhar,1985). The three axioms and their applicability to the prioritization scheme are discussed below.

#### The First Axiom: Ordering and Transitivity

This axiom requires that the person either prefers one of two risky prospects (a) and (b) or is indifferent between them. (It is presumed that people can order prospects). The second part of the axiom requires that the decision maker should be transitive in his choices. This implies that if a person prefers lottery A to lottery B (or is indifferent between them) and prefers lottery B to lottery C (or is indifferent between them), then he should prefer lottery A to C (or is indifferent between them).

This axiom was obeyed in the suggested prioritization scheme. For example, if pH is more important than electrical conductivity and electrical conductivity was more important than root temperature, then pH was more important than root temperature.

#### The Second Axiom: Substitutability (Independence)

If some of the prizes in a lottery are replaced by other prizes such that the decision maker is indifferent between each new and the corresponding original prize, then the decision maker should be indifferent between the original and the modified lotteries.



This axiom was also obeyed in the suggested prioritization scheme. For example, if in one scenario a pH with a utility of 0.7 was ordered first, followed by a RH of utility of 0.55, and an EC of utility 0.3, and in another scenario a root temperature with utility of 0.7 was ordered first, followed by a RH with utility of 0.55, and an EC of utility 0.3, both scenarios take exactly the same ordering.

The above two axioms are the two principles of consistent behavior.

### The Third Axiom: Continuity

If the decision maker prefers  $a$  to  $b$  to  $c$ , a subjective probability  $p(a)$  exists other than zero, or one such that he is indifferent between  $b$  and a lottery yielding  $a$  with probability  $p(a)$  and  $c$  with probability  $1-p(a)$ . This implies that if faced with a risky prospect involving a good and a bad outcome, the decision maker will take the risk if the chance of getting the bad outcome is low enough. This means that if  $EC > pH > RT$  in terms of prioritization, then the grower will decide to deal with EC first then pH then RT.

The above axioms together imply the existence of a *utility function*  $u$  that has two properties. First, the utility function preserves the order of preferences among risky prospects; that is,  $a$  is preferred to  $b$  if and only if the utility of  $a$  is greater than the utility of  $b$ . Second, the utility function is "linear in probabilities": that is,

$$u(p(a)a+(1-p(a))b) = p(a)u(a)+(1-p(a))u(b) \quad (4.1)$$

The folding back procedure of a decision tree relies on this linearity property.

#### 4.4 The Decision Tree

The suggested prioritization procedure can be graphically represented in the schematic form of a decision tree as shown in Figure 4.2. The first part of the decision tree is a decision node with five branches. Each branch represented one of the five key tests that were identified from the experiential and the literature studies. These five key tests included pH, electrical conductivity (EC), root temperature (RT), air temperature (AT), and relative humidity (RH). The second part of the decision tree comprised of a chance node with two additional branches. This chance node represented the probability ( $p$ ) that the given test value could produce the best quality crop.

At the end of the tree is the utility value corresponding to each path of the decision tree. A utility of (1) is given for the path producing the best crop, and a utility of (0) is given for the path producing any other crop.

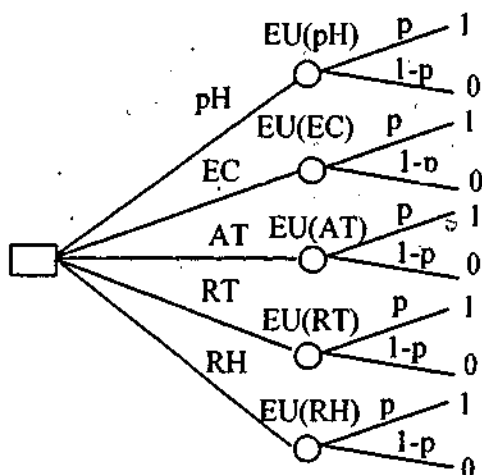


Figure 4.2 Decision Tree

The averaging out and folding back procedure was carried out by applying Equation 4.1 resulting in what is called the expected utility values for each of the five tests branches. The branch with the highest expected utility value was assumed to be the one most likely to produce the best quality crop. The test result with the lowest expected utility value was assumed to be at the top of the prioritization list to be dealt with first.

For each test, the various test results together with the corresponding expected utility values were plotted against each other to form a utility function, herein referred to as the Growth Activity Function (GAF). The developed GAFs for the five key tests are presented in the next chapter.

Inside the HYTODMOD, there was a subroutine for each of the GAF functions of the five key tests. Using linear interpolation, the respective subroutines identified the corresponding expected utility value with any of the entered test results. This expected utility value indicated how far a given variable value was from the optimum growing range of the variable.

**CHAPTER V**  
**DEVELOPMENT OF**  
**GROWTH ACTIVITY FUNCTIONS**

**5.1 Introduction**

The literature review carried out in this dissertation, the knowledge learned from the CropKing grower's school, the experience gained during the experiential growing experiment, and the discussions with experts in the area of hydroponic tomato production were all used in conjunction with the utility theory of decision analysis to develop Growth Activity Functions (GAF) for the five key tests identified earlier. This chapter describes the analysis of the literature that was used in developing the GAF. It also demonstrates the GAF and the criteria followed in developing each one.

**5.2 Analysis of Literature**

The literature review, identifying key tests and the effect of various levels on producing the highest yield, highest quality crop were compiled into five sets of tables, one for each of the five key tests. These Tables 5.1 through 5.5, for root temperature, electrical conductivity, pH, air temperature, and relative humidity, allowed assigning utility values for given key test levels. In addition, the descriptive information in the tables points out the interaction of one key test to another, like the interaction between root temperature and air temperature.

Table 5.1 Summary of the Root Temperature Studies for Greenhouse Grown Tomatoes

10°C	12°C	15°C	17°C	18.3°C
Shoot elongation was sharply reduced. Caused deficiencies to some nutrients.	The plant dry weight and water uptake was 70 % less than that at 22°C.	The disease spread and the plants died.	The minimum temperature during the vegetative, early, and mature fruiting phases should be between 16.7 and 17.2°C.	Less than 20°C did greatly impaired the plant ability to absorb nutrients and take up water.
		Caused deficiencies to some nutrients.	Leaf area increased with the soil temperature between 17 and 30°C.	
		The optimum range for vegetative phase was between 15 and 18°C. The optimum range for early and mature fruiting phases was between 16 and 20°C.		
Growth rate reduced at a soil temperature of < 20°C.				
Generative development was not greatly influenced by soil temperature. Leaves and roots were not looking good.				
Majority of macro and micro nutrient uptake increased from 10 to 26.7°C.				

Table 5.1 (continued)

20°C	22°C	24°C	25°C	26.1°C
Difference between 20 and 30°C were small and irregular.  Optimum range during seedling phase between 19 and 20°C. /	The optimum range for vegetative, early and mature fruiting phases is between 21 and 22.2°C.	Crop production could be maintained under 9°C night temperature and 24°C root temperature.	The plants remained symptomless. root dry weight & shoot dry weight, rate of shoot growth, pH, and water use peaked at 25°C. Optimum temperature during seedling phase for uptake of the majority of mineral elements and all plant growth responses. Maximum temperature during vegetative, early and mature fruiting phases should be 25.6°C.	At 26.1°C and above roots were looking good.
Optimum range for germination and seedling phases.				
Optimum range for germination.				

Table 5.1 (continued)

26.5°C	26.7°C	30°C	32.2°C	37.8°C
<p>This was the optimum root temperature based on dry weight at air temperatures of 16 and 21°C.</p> <p>It was the optimum root temperature based on root length at air temperatures of 11, 16, and 21°C.</p>	<p>Nutrient uptake was peaked at 26.7°C.</p>	<p>Above 30°C there was a great impairment in plant ability to absorb nutrient and take up water.</p> <p>Optimum temperature for seedling growth based on fresh and dry weight, and leaf area.</p>	<p>Optimum was achieved at 32°C and at air temperature 11°C based on dry weight.</p> <p>Macro and micro nutrient uptake decreased at 32.2 and 37.8°C Same trend occurred to the root dry weight and shoot dry weight.</p> <p>Above 32.2°C the roots were killed.</p>	<p>Shoot elongation was sharply reduced.</p> <p>Caused deficiencies in some nutrients.</p>

Table 5.2 Summary of the Electrical Conductivity Studies  
for Greenhouse Grown Tomatoes

300 $\mu$ mhos/cm	1000 $\mu$ mhos/cm	1800 $\mu$ mhos/cm	2000 $\mu$ mhos/cm
<p>Best during the day with 10000 <math>\mu</math> mhos/cm at night for vegetative growth measured as fruit weight, dry weight, leaf area compared to: constant 2000, constant 6000, and 10000 during the day and 0.3 <math>\mu</math> mhos/cm at night.</p>	<p>Positive response of plants to increasing levels of N was obtained at this level.</p>		<p>Total plant dry weight, proportional distribution of dry matter into fruit, vegetative shoot and roots were unaffected at this level.</p>
			<p>shoot dry weight was highest compared to 6000 and 10000 micromhos/cm. Percent of blossom end rot was significantly less than at 6000 and 10000 micromhos/cm. This level was not the best for root dry weight</p>
<p>Recommended range during germination and early growth. For the same stage an EC of 1500 micromhos/cm is recommended in warm weather conditions.</p>			



Table 2 (continued)

2300 $\mu$ mhos/cm	2500 $\mu$ mhos/cm	3000 $\mu$ mhos/cm	3500 $\mu$ mhos/cm	4000 $\mu$ mhos/cm
	At this level greatest leaf area, dry weight, and root dry weight was achieved at 22°C RT, and 65% RH.	Saline water irrigation of 3100 EC level produced 42% average production decrease, 33% decrease on average fruit weight, and 12% reduction in fruit number. This level affected vegetative development by reducing plant height, their vigor, and their stem thickness.		Total plant dry weight, proportional distribution of dry matter into fruit, vegetative shoot and roots were unaffected at this level.
		Produced highest yield among 8000 and 12000 micromhos/cm		
Optimum range for seedling, vegetative growth, early fruiting, and mature fruiting stages.			Optimum range during low light conditions for the seedling, vegetative, early fruiting, and mature fruiting stages.	
		Recommended normal level.		

Table 5.2 (continued)

6000 $\mu$ mhos/cm	8000 $\mu$ mhos/cm	8500 $\mu$ mhos/cm
<p>Total plant dry weight, proportional distribution of dry matter into fruit, vegetative shoot and roots were unaffected at this level.</p> <p>shoot dry weight was less compared to 2000 micromhos/cm.</p> <p>Percent of blossom end rot was significantly higher than at 2000 micromhos/cm.</p> <p>root dry weight was best at this level.</p>	<p>Loss of yield occurred at this level.</p> <p>Dry matter content increased by 20% when EC increased from 2000 to 8000 micro:mhos/cm.</p> <p>Total height decreased from 2.0 <math>\mu</math> mhos/cm.</p> <p>Quality and composition of the fruit was improved by increasing salinity from 3000 to 8000 <math>\mu</math> mhos/cm.</p> <p>Highest yield was obtained at 3000 <math>\mu</math> mhos/cm compared to 8000 and 12000 <math>\mu</math> mhos/cm.</p> <p>Recommended normal level.</p>	<p>At 22°C RT, and 65% RH the leaf area, dry weight, and root dry weight at this level was less than at 2500 <math>\mu</math> mhos/cm.</p>

Table 5.2 (continued)

9000 $\mu$ mhos/cm	10000 $\mu$ mhos/cm	12000 $\mu$ mhos/cm	17000 $\mu$ mhos/cm
Increased N was ineffective to counteract adverse effects due to high salt concentration.	Total plant dry weight was reduced by 19% from 2000 $\mu$ mhos/cm.	Lowest yield occurred at this level compared to 3000 and 8000 $\mu$ mhos/cm.	Fruit weight of mature fruiting was 40% less than at 2000 $\mu$ mhos/cm.
	Best at night with 3000 $\mu$ mhos/cm during the day.		
	Raising EC from 2 to 10 $\mu$ mhos/cm decreased shoot dry weight, increase % of blossom end rot, decreased root dry weight.		The increase in fruit weight was markedly reduced. The % of dry matter of the fruit was markedly increased by high salinity.
	Loss of yield occurred at this level.		

Table 5.3 Summary of the pH Studies for Greenhouse Grown Tomatoes

4.0	5.5	6.0	6.5	7.0	8.0
Yields were reduced below 6.0.		pH of 6.0 was maintained for the first five days after transplanting.	Best marketable yields between 6.5 and 6.9.	Optimal pH.	Fewer fruits were markedly set.
There was a sign of hydrogen ion injury. Concentrations of Mg and N in the tops of tomato were inadequate for optimal growth.	From 5.2 - 5.5 in the feeding solution. From 5.5 - 5.8 in the perlite bag.				
Between pH 4.0 and 7.0 the plant dry weight increased by 50%.					
Maximum or near maximum growth achieved in this range.					

Table 5.4 Summary of the Air Temperature Studies for Greenhouse Grown Tomatoes

9°C	10°C	12°C	14°C	15°C	15.5°C	16°C
Seeds failed to emerge.						
At the vegetative phase the range should be from 12-15°C at night			During early and mature fruiting phase, the range should be from 14-16°C at night.			
Recommended day temperature.(15.5-21.1) by some studies conducted before 1964.			Recommended day temperature.(15.5-21.1)°C by some studies conducted before 1964.			

Table 5.4 (continued)

17°C	17.2°C	17.8°C	18°C	18.3°C	19°C
17°C reduced growth compared to 21 and 25°C. It also, resulted in a late but much flowering. After 3 weeks there were no open flowers. The total dry weight was low.	For all phases, the minimum temperature should be 17.2°C at night.	The highest growth rate if the night temperature does not fall below 17.8°C and the day does not lower than 20°C.	At 24°C seeds had an earlier and higher emergence than at 18°C.	Yield at 18.3°C produced 30% greater yield than at 26.5°C.	
The rate of flowering rate is enhanced by the 24 h temperature (17, then 19, then 21, and then 23°C)				From 2nd week - transplanting the optimum range should be from 18.3-20°C at night.	
			For seedling, optimum range from 18-20°C.		
			For vegetative phase from 18-22°C during the day.		

Table 5.4 (continued)

20°C	21.1°C	22°C	23°C	24°C
From 2nd week through transplanting, optimum range should be 18.3-20°C at night.	At 21 & 25°C, the % of open flowers in 1st truss was 15 & 50. At those temperatures, plants showed relatively thin stems, and yielding capacity was reduced.	Fruit yield ranged between 1&3 per truss for the 35/25°C day/night temperature and between 3 & 6 fruits per truss for the 22/18°C day/night temperature.	From the 4th day through the 2nd week after seedling the optimum is 23.3°C during the day, and 20°C at night	At 24°C seeds had an earlier and higher emergence than at 18°C.
From 4th day - 2 weeks after seedling the optimum is 23.3°C during the day, and 20°C at night.	From 2nd week - transplanting the range should be 21.7-22.8°C on cloudy days.	For early and mature fruiting phase the day temperature should be from 22-28°C.	For vegetative, early fruiting, and mature fruiting the range should be 22.8-25.6°C on sunny days.	
20/15°C gave higher truss capacity, later fruit set, lower numbers of fruits larger than 30 mm as well as larger than 5 mm, and lower fresh weights than the 35/18°C day/night temperature.				
For vegetative, early fruiting, and mature fruiting the range should be 20-21.1°C on cloudy days.				

Table 5.4 (continued)

25°C	26.1°C <sup>s</sup>	26.5°C	27°C
From 2nd week - transplanting, the range should be 25.0-25.6°C on sunny days		Shading reduced proportion of non uniformly colored fruit at 26.5°C.	Pollen germination was best at 27°C.
At 21 & 25°C the percent of open flowers in 1st truss was 15 & 50 %. At those temperatures plants showed relatively thin stems, and yielding capacity was reduced.			Ovules under 33/23°C day/night temperature were significantly more receptive early in development than those under low temperature regime; 27/4°C day/night
For vegetative, early fruiting, and mature fruiting the range should be 22.8-25.6 °C on sunny days			
Optimum range for rapid germination for the first 4 days.			
For early and mature fruiting phase the range should be from 22-28°C during the day..			



Table 5.4 (continued)

33°C	35°C
<p>In the fully opened flowers stigma levels were highest at 33/23°C day/night temperature.</p> <p>Ovules under 33/23°C day/night temperature were significantly more receptive early in development than those under low treatment; 27/4°C day/night.</p>	<p>35/25°C day/night temperature produced twice stem growth as the 22/18°C but thin stems and many trusses with weak flowers.</p> <p>Fruit yield ranged between 1&amp;3 per truss for the 35/25°C day/night temperature and between 3 &amp; 6 fruits per truss for the 22/18°C day/night temperature.</p> <p>35/18°C gave lower truss capacity, earlier fruit set, higher numbers of fruits larger than 30 mm as well as larger than 5 mm, and higher fresh weights than the 20/15°C day/night temperature.</p>

Table 5.5 Summary of the Relative Humidity Studies for Greenhouse Grown Tomatoes

50%	55%	64%	87%
<p>Better for growth of young leaves and Ca distribution compared to 95% RH.</p>	<p>Plant tissues at this level had higher Ca concentration than those grown at RH of 95%</p>	<p>Ca intake was less at this RH at night than at RH of 87%.</p>	<p>Ca intake was greater at this RH at night than at RH of 64%</p> <p>Final yield was significantly lower at RH of 82/73% (day/night) than at RH of 82/72% (day/night)</p>
<p>The range between 70 and 80% is recommended in the area around the growing media during the germination and early growth stage. For pollination the best range of RH is between 60 and 80%.</p>			

Table 5.5 (continued)

88%	93%	95%	100%
RH must be below 90% from vegetative until termination stages.		Growth of young leaves was disturbed and the plants showed symptoms of Ca and B deficiency.	Recommended level of RH around the seed during germination and early growth stage.
Caused significant reductions in leaf area. Also, reduced fruit quality.		Blossom end rot developed at the distal end on young green fruit.	
		Plant tissue had lower Ca concentration than that grown at RH of 55%.	

### **5.3 Growth Activity Functions**

The following criteria were followed in forming the Growth Activity Functions (GAF) using the literature information from Tables 5.1-5.5 and the experimental study:

1. If there was a consensus that the level of the key test could produce high yield, high quality fruit, then the key test level was assigned a utility value of one (consensus refers to majority of agreement among literature and the experimental study).
2. If the literature and the experimental studies showed a poor quality crop for the given key test level, then the level was assigned a utility value of zero.
3. If for the key test level there was no obvious consensus on crop performance, then the most recent literature and the experimental study were used to assign utility values between 0 and 1.

#### **5.3.1 Hydrogen Ion Concentration of the Feeding Solution**

Figure 5.1 shows the developed GAF for the Hydrogen Ion Concentration (pH) over the total range 3 - 10. Since the pH is not affected by weather conditions and its optimum range does not vary from one growth stage to another, one GAF was developed for all the growth stages. Analysis of data for the crop response to pH using the criteria for the GAF resulted in a utility value of zero below pH of 3 or above pH of 10. A utility value of 1 was assigned to pH between 5.5 and 6.5. Based on criterion #3 above, a utility value of 0.2 was assigned to pH of 4 and pH of 8 as shown in Figure 5.1.

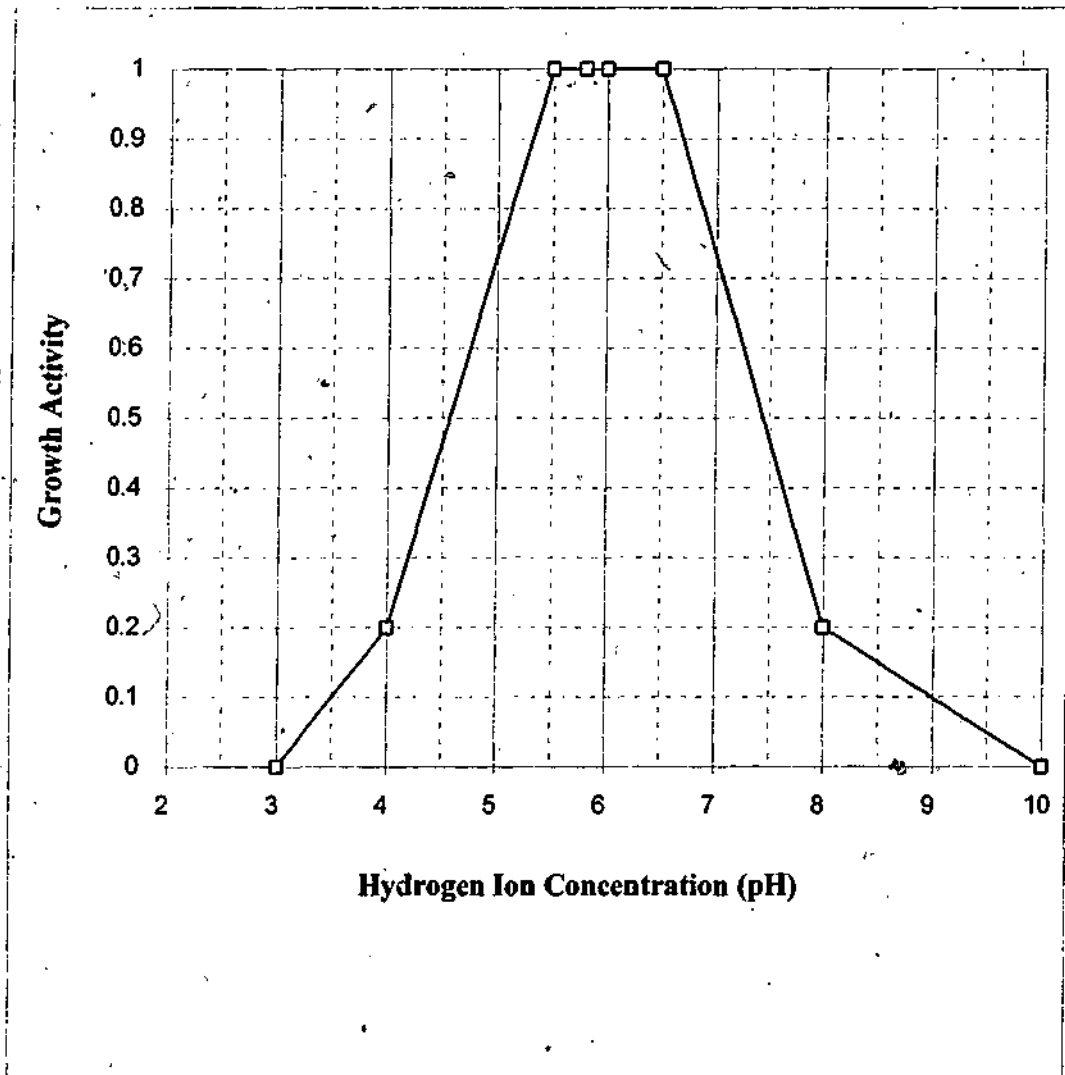


Figure 5.1 Tomato Growth Activity Function for Hydrogen Ion Concentration from Germination and Early Growth Stage until Termination Stage for Producing Best Crop.

### **5.3.2 Root Temperature**

Figures 5.2 and 5.3 show the GAF developed for the Root Temperature (RT) over the total range of 10 - 40°C. It was observed that the optimum range of RT for the germination and early growth stage and the seedling stage is higher than the one desirable between the vegetative and the termination stages. This lead to the development of two GAFs for RT. Analysis of data for crop response to RT using the criteria for the GAF resulted in a utility value of zero for RT below 10°C or for RT above 40°C for all growth stages. A utility value of 1 was assigned to RT between 25 and 26.7°C for the germination and early growth stage and the seedling stage (Figure 5.2). For the stages from vegetative until termination, a utility value of 1 was assigned to RT between 20 and 22.2°C (Figure 5.3). Based on criterion #3 above a utility value of 0.1 was assigned to RT of 15°C during the germination and early growth stage and the seedling stage (Figure 5.2).

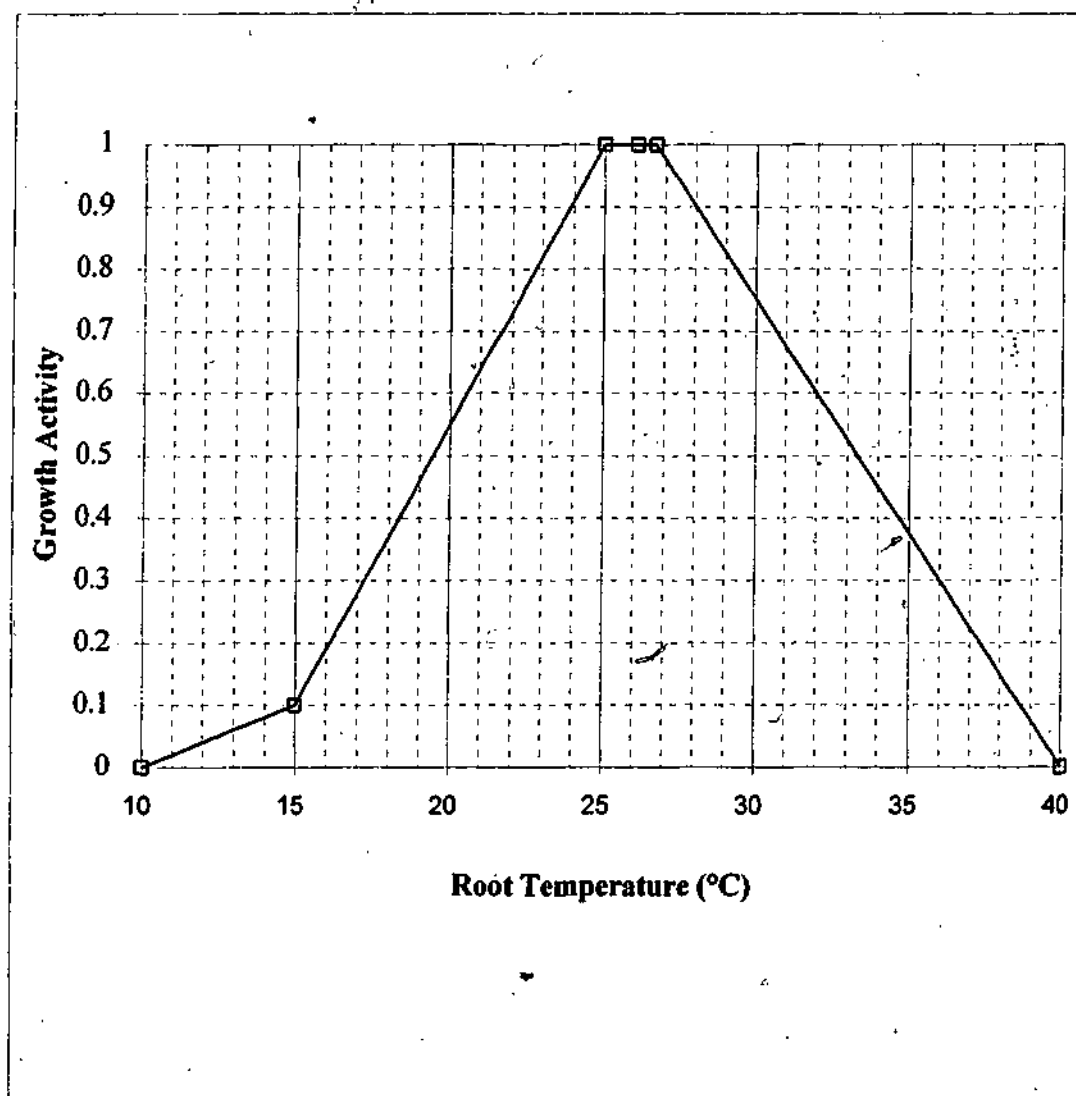


Figure 5.2 Tomato Growth Activity Function for Root Temperature from Germination and Early Growth stage until Seedling Stage for Producing Best Crop.

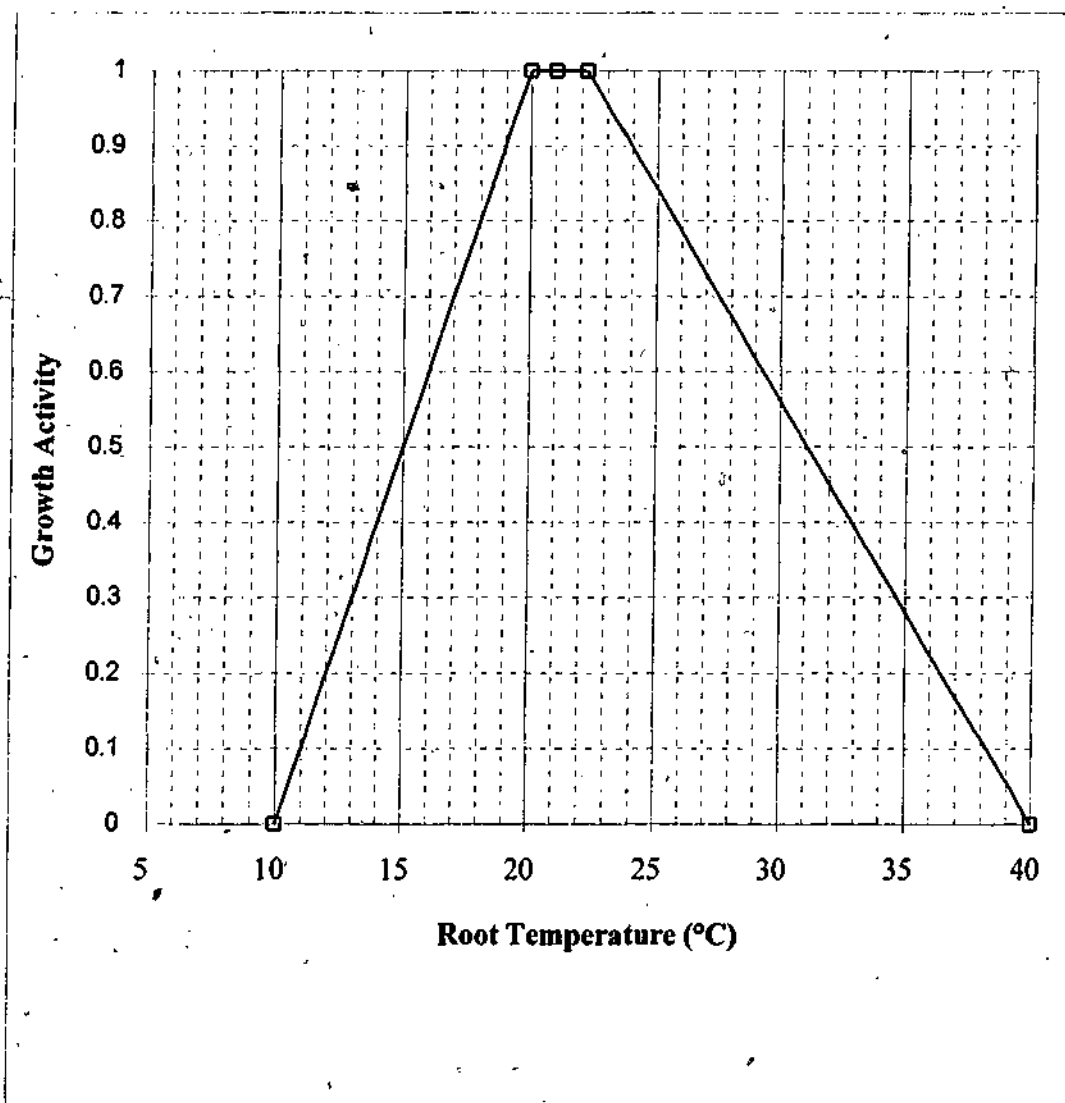


Figure 5.3 Tomato Growth Activity Function for Root Temperature from Vegetative Stage until Termination Stage for Producing Best Crop.



### 5.3.3 Air Temperature

Four GAFs were developed for the air temperature (AT). One was for the germination and early growth stage over the total range of 9 - 35°C as shown in Figure 5.4. Three GAFs were for the seedling until termination stages over the total range of 10 - 40°C. The last three are: one for night, one for sunny, and one for cloudy weather conditions as shown in Figures 5.5, 5.6, and 5.7 respectively.

Analysis of data for crop response to AT using the criteria for the GAF resulted in a utility value of zero below AT of 9°C or above AT of 35°C for the germination and early growth stage (Figure 5.4). From seedling until termination stages, a utility value of zero was assigned to AT below 10°C or above 40°C (Figures 5.5, 5.6, and 5.7).

A utility value of 1 was assigned to AT between 24 and 26.1°C for the germination and early growth stage (Figure 5.4). From seedling until termination stages a utility value of 1 was assigned to AT between 18.3°C and 20°C for the night temperature (Figure 5.5), to AT between 22.8°C and 25.6°C for a sunny day temperature (Figure 5.6), and to AT between 20°C and 23.3°C for a cloudy day temperature (Figure 5.7). Based on criterion #3 above, a utility value of 0.5 was assigned to night AT of 17.2°C from seedling until termination stages (Figure 5.5). Two key factors were found to be detrimental in selecting the growing optimum ranges for the AT throughout the different growth stages. One was the temperature range for the best tomato plant growth. The second was the temperature range best for energy savings at the different growth stages and weather conditions.

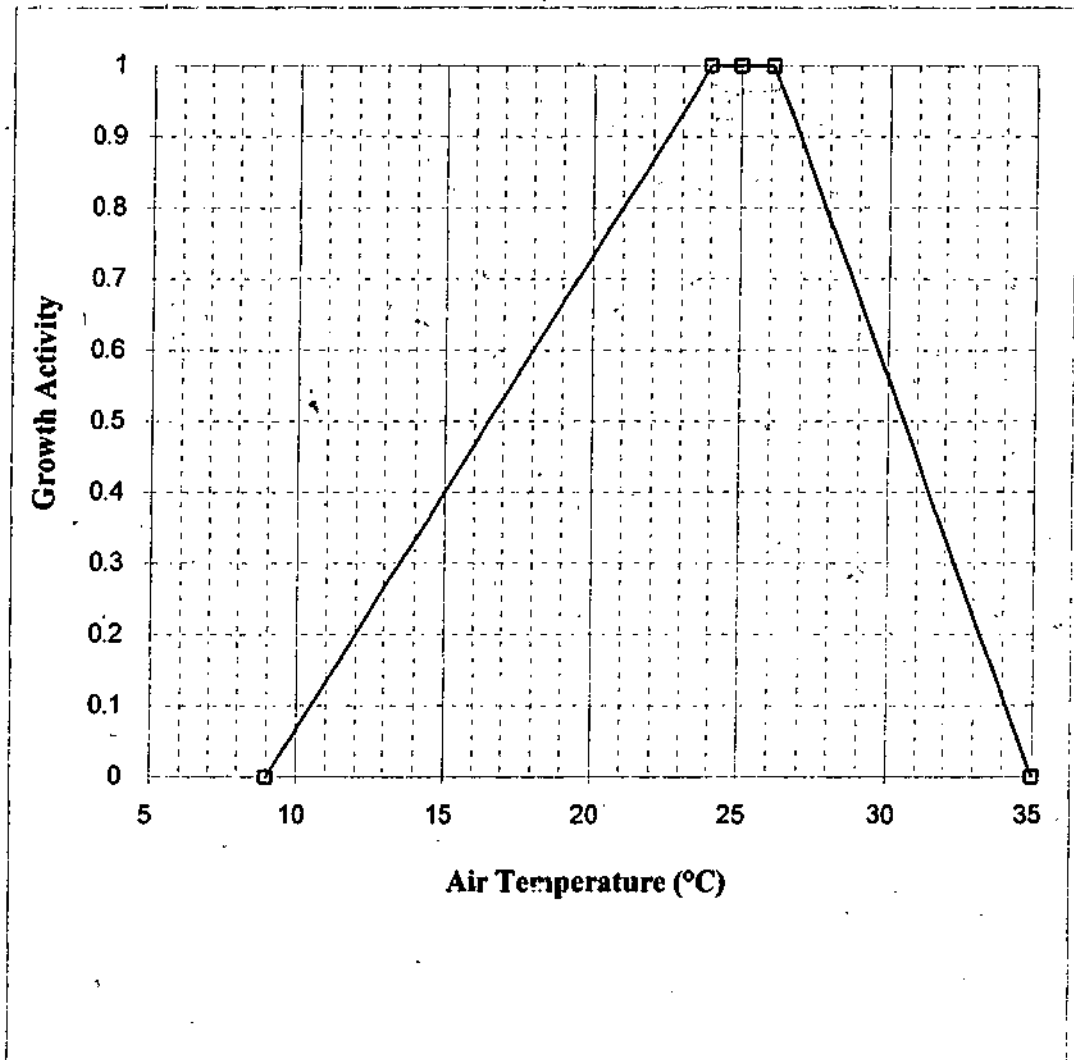


Figure 5.4 Tomato Growth Activity Function for Greenhouse Air Temperature during Germination and Early Growth Stage for Producing Best Crop.

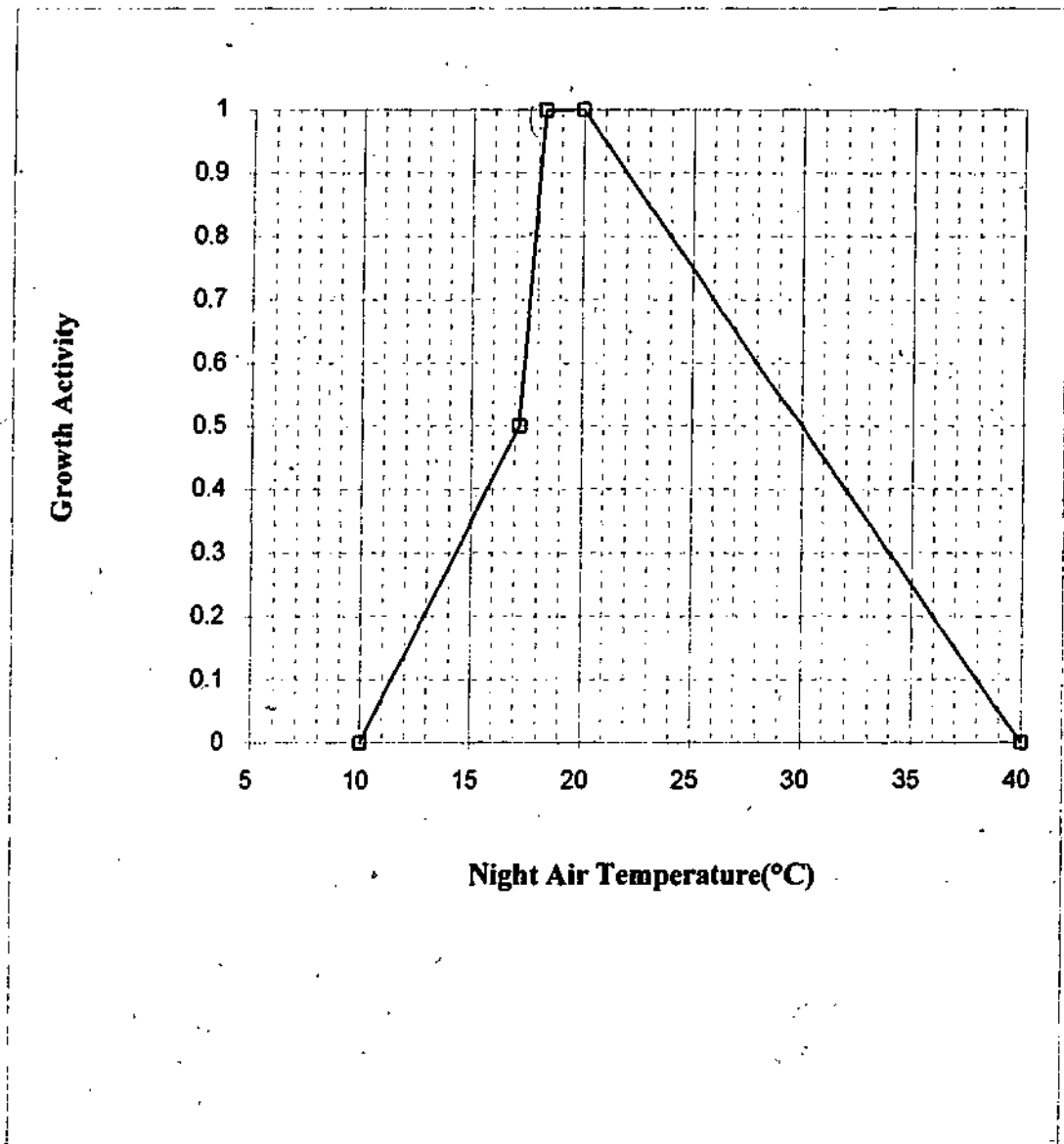


Figure 5.5 Tomato Growth Activity Function for Greenhouse Night Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop.

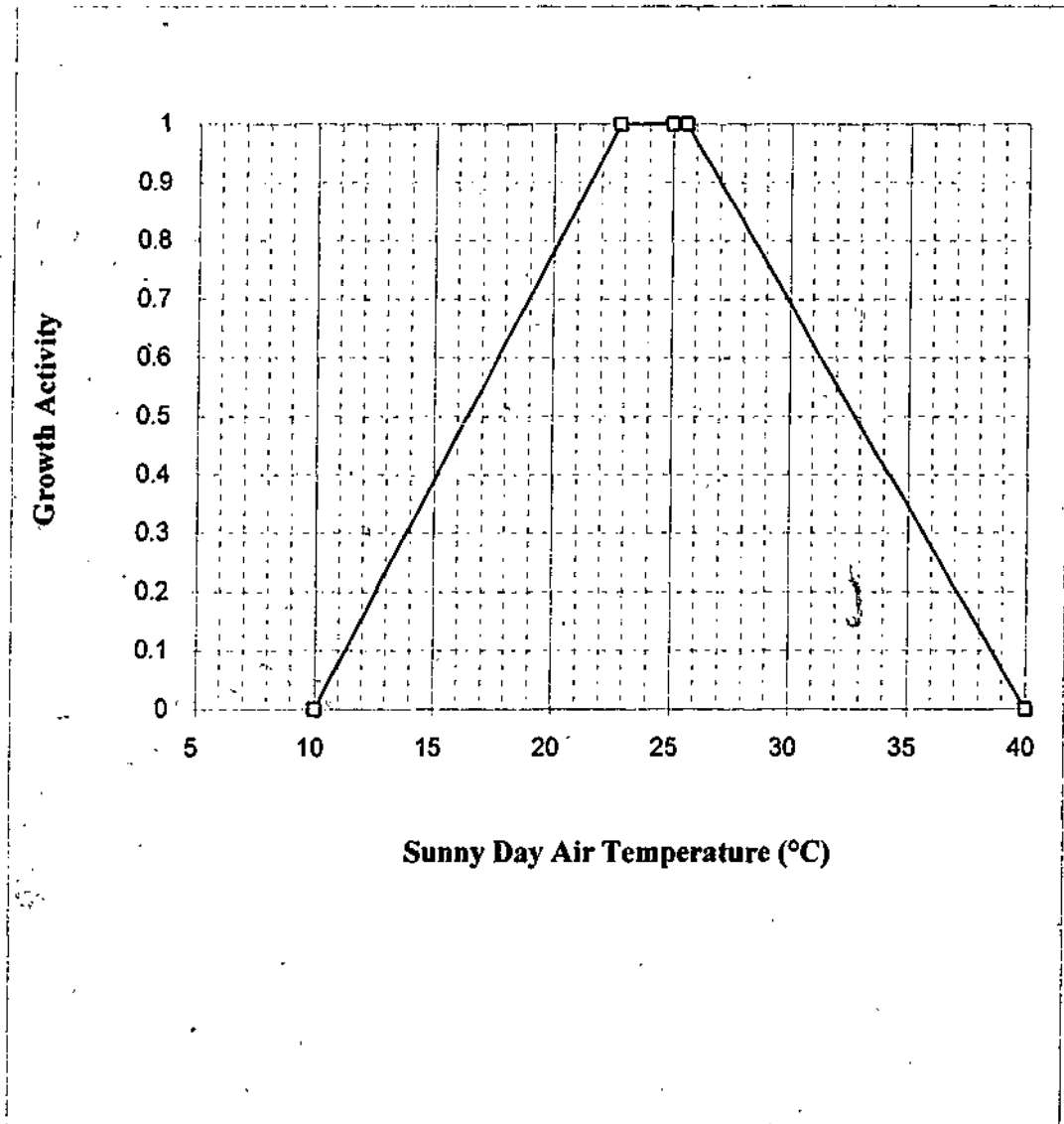


Figure 5.6 Tomato Growth Activity Function for Sunny Day Greenhouse Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop.

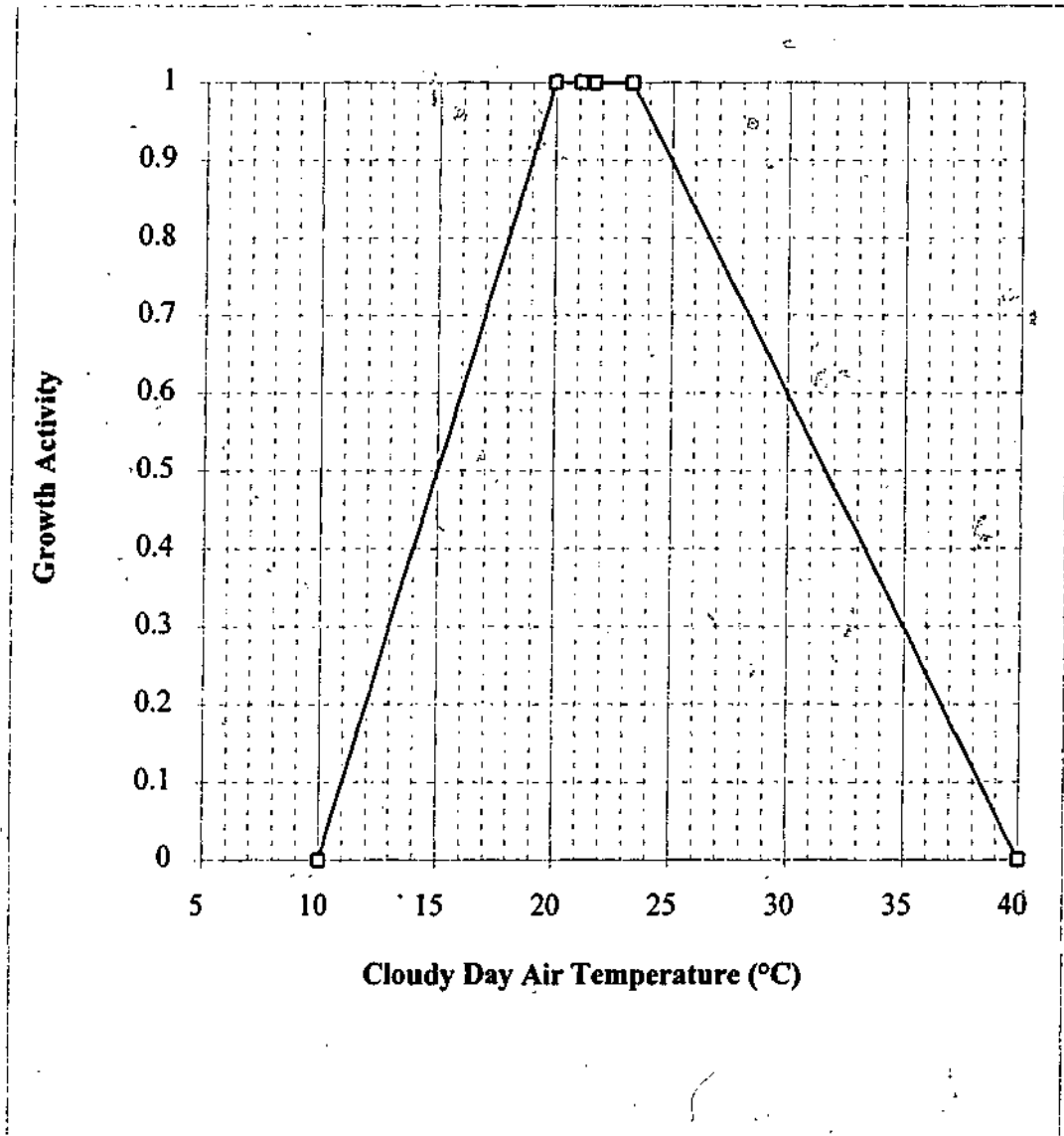


Figure 5.7 Tomato Growth Activity Function for Cloudy Day Greenhouse Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop

### **5.3.4 Electrical Conductivity of the Feeding Solution**

Three GAFs were developed for the Electrical Conductivity (EC): one for the germination and early growth stage (Figure 5.8), one for the seedling until termination stages for sunny weather conditions (Figure 5.9) and another for the seedling until termination stages for cloudy weather conditions (Figure 5.10). Since the preferred EC is greatly affected by solar radiation levels, the GAFs for seedling until termination stages were divided into two functions: one for cloudy and one for sunny weather conditions. Analysis of data for crop response to EC using the criteria for the GAF resulted in a utility value of zero for EC of 0  $\mu\text{mhos/cm}$  or above EC of 5000  $\mu\text{mhos/cm}$  for the germination and early growth stage (Figure 5.8), and for EC below 1000  $\mu\text{mhos/cm}$  or above 12000  $\mu\text{mhos/cm}$  for seedling until termination growth stages (Figures 5.9 and 5.10). A utility value of 1 was assigned to EC between 1800 and 2000  $\mu\text{mhos/cm}$  for the germination and early growth stage (Figure 5.8), and between 2300 and 2500  $\mu\text{mhos/cm}$  for the seedling until termination stages on a sunny day (Figure 5.9), and between 3500 and 4000  $\mu\text{mhos/cm}$  for the seedling until termination growth stages on a cloudy day (Figure 5.10).

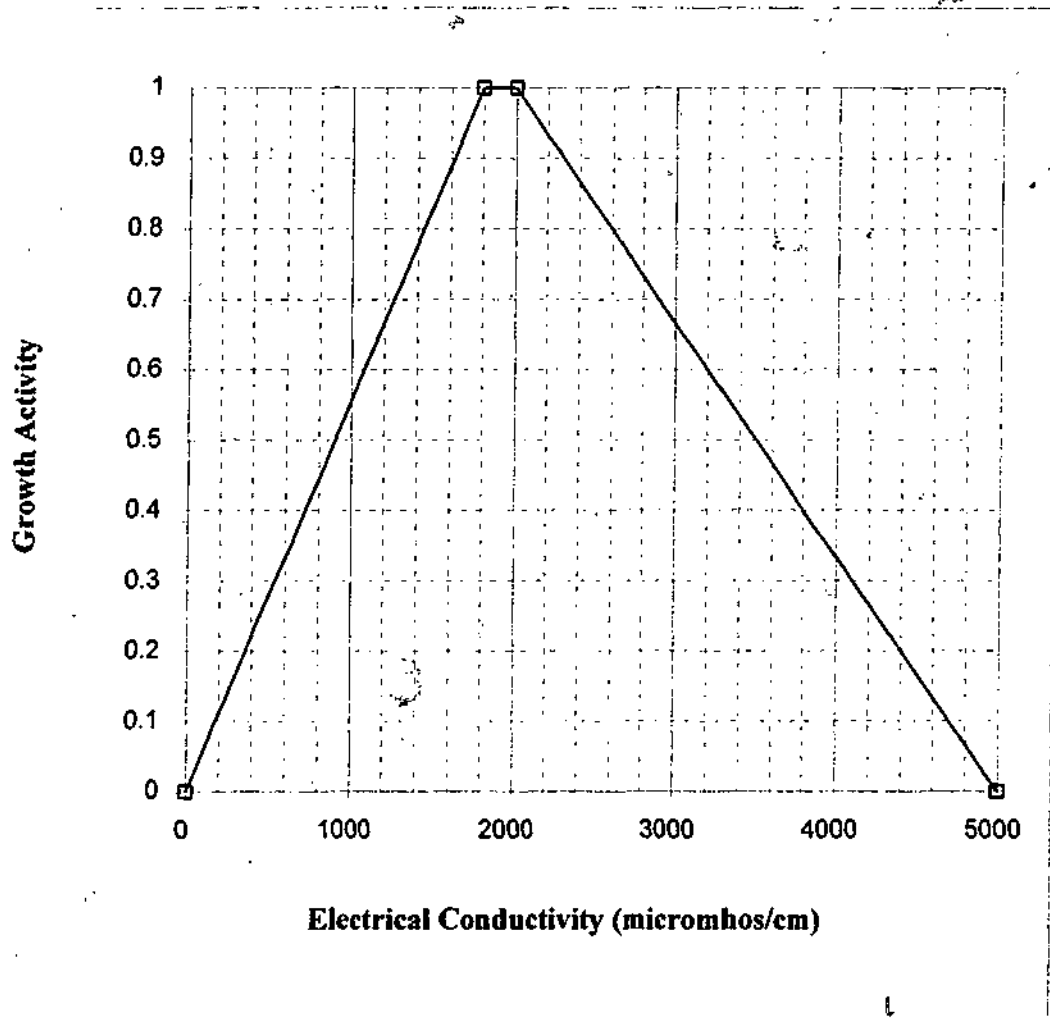


Figure 5.8 Tomato Growth Activity Function for Feeding Solution Electrical Conductivity during Germination and Early Growth Stage for Producing Best Crop.

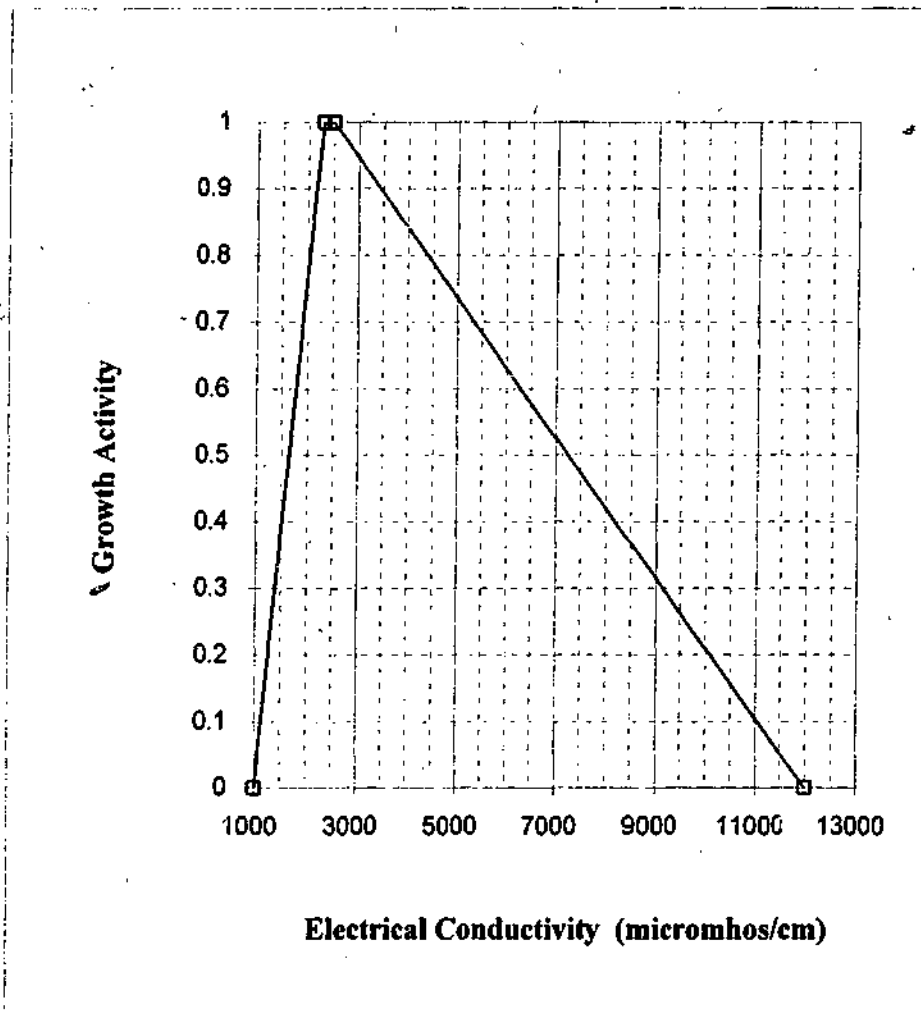


Figure 5.9 Tomato Growth Activity Function for Sunny Day Feeding Solution Electrical Conductivity from Seedling Stage until Termination Stage for Producing Best Crop.



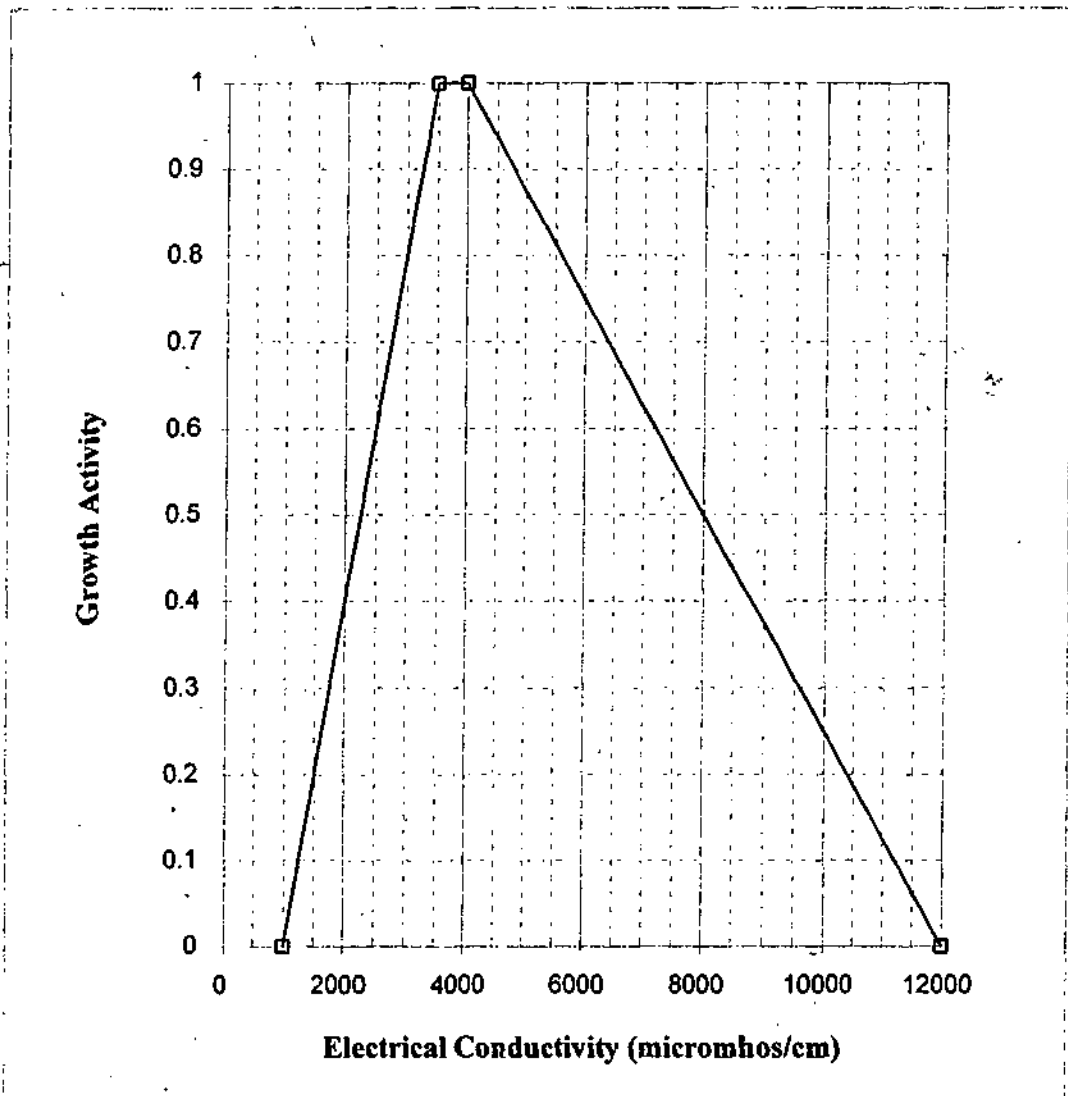


Figure 5.10 Tomato Growth Activity Function for Cloudy Day Feeding Solution Electrical Conductivity from Seedling Stage until Termination Stage for Producing Best Crop.

### **5.3.5 Relative Humidity**

Three GAFs were developed for the Relative Humidity (RH): one for the germination and early growth stage (Figure 5.11), one for the seedling stage (Figure 5.12), and one for the vegetative until termination growth stages (Figure 5.13). Analysis of data for crop response to RH using the criteria for the GAF resulted in a utility value of 0 below RH of 60% for germination and early growth stage (Figure 5.11), and below RH of 40% for the seedling stage (Figure 5.12), and below RH of 30% and near RH of 100% from vegetative until termination stages (Figure 5.13). A utility value of 0.6 was assigned to RH of 100% for the germination and early growth stage as well as for the seedling stage (Figures 5.11 and 5.12 respectively). A utility value of 1 was assigned to RH between 75% and 85% for germination and early growth stage (Figure 5.11), to RH between 75% and 80% for the seedling stage (Figure 5.12), and to RH between 60% and 80% for the stages from vegetative until termination (Figure 5.13).

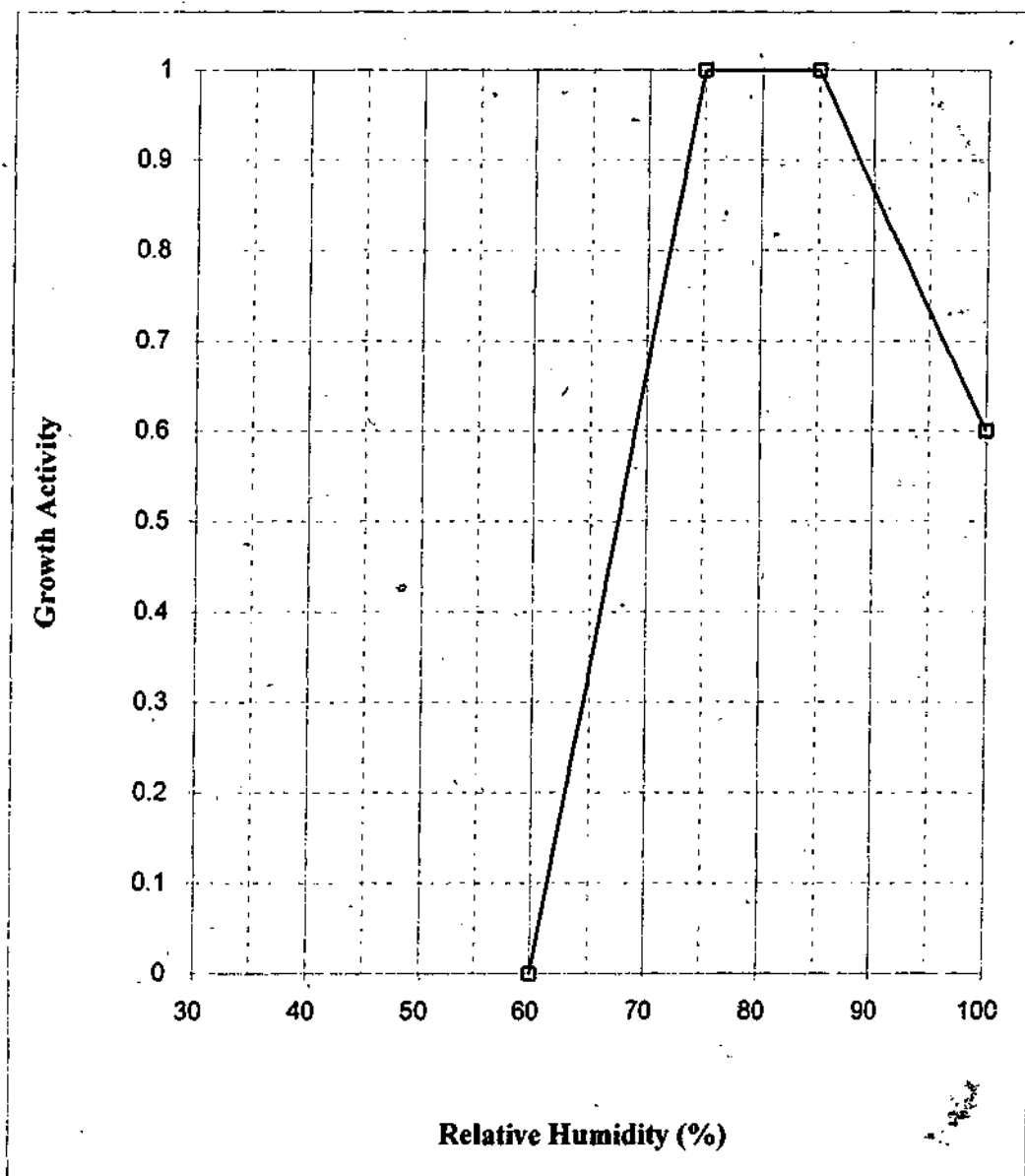


Figure 5.11 Tomato Growth Activity Function for Greenhouse Air Relative Humidity during Germination and Early Growth Stage for Producing Best Crop.

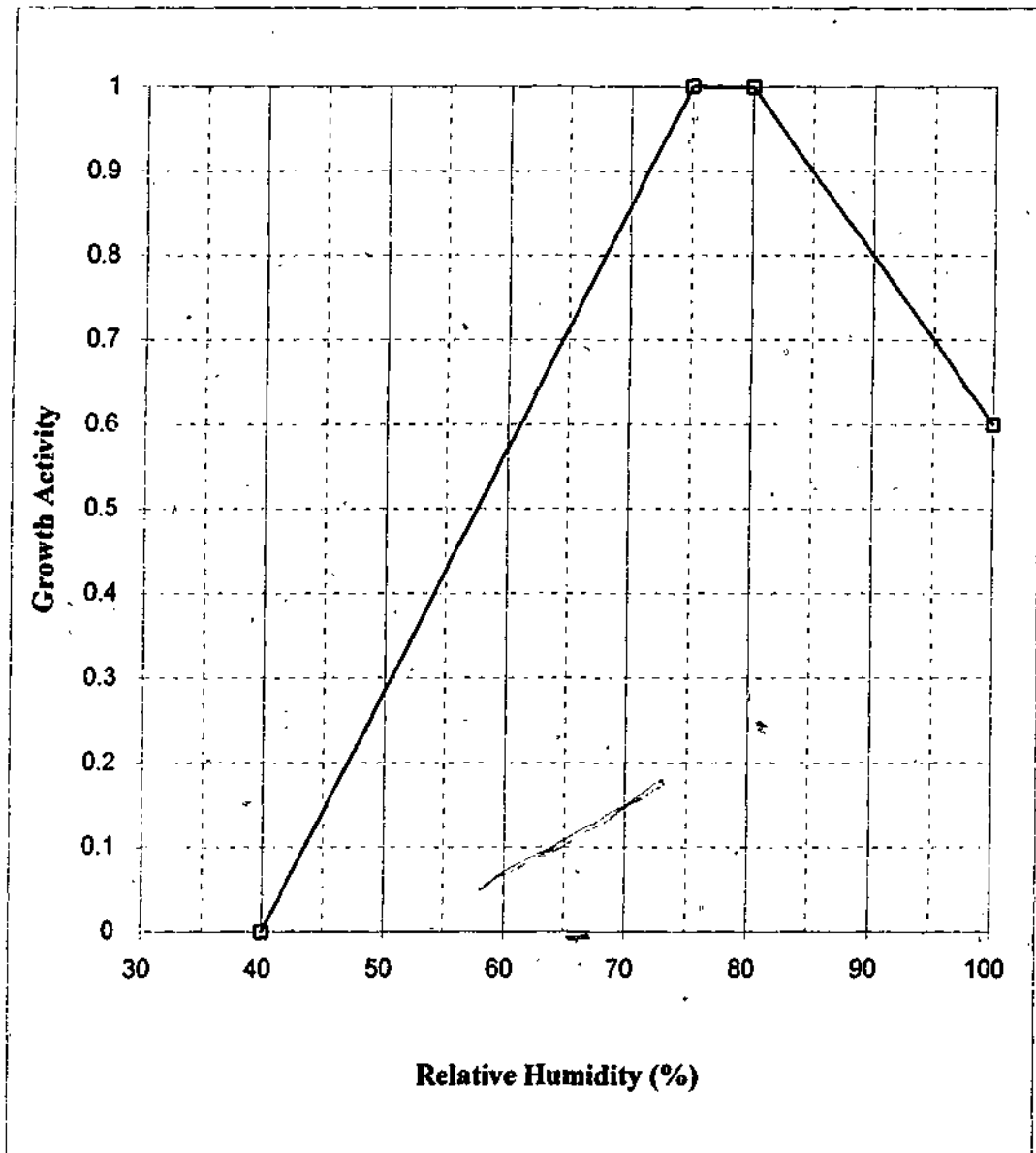


Figure 5.12 Tomato Growth Activity Function for Greenhouse Air Relative Humidity during Seedling Stage for Producing Best Crop.

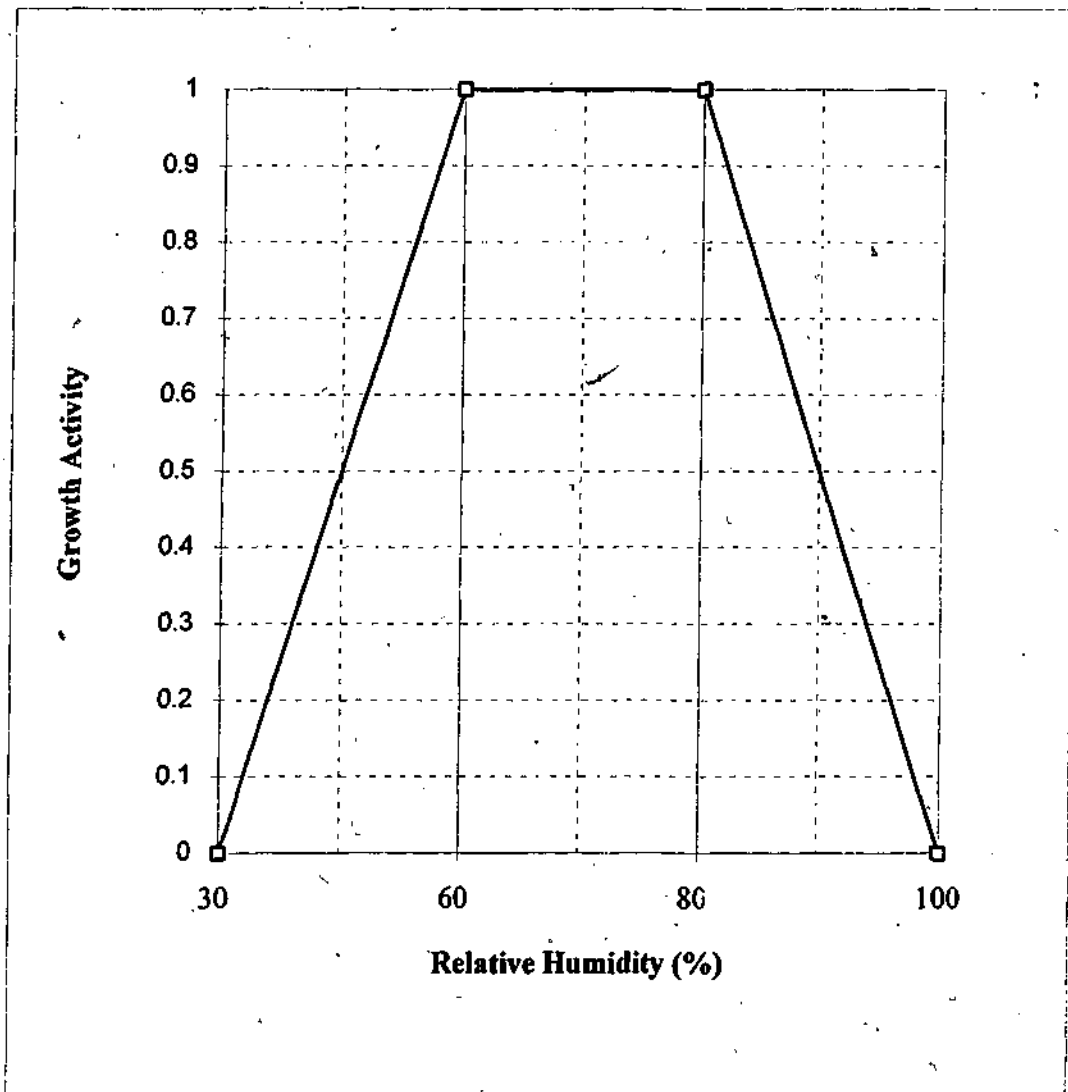


Figure 5.13 Tomato Growth Activity Function for Greenhouse Air Relative Humidity from Vegetative Stage until Termination Stage.

## **CHAPTER VI**

### **VALIDATION OF DECISION MATRIX**

#### **6.1 Introduction**

This chapter describes the methodology used to test the validity of the decision model and the Growth Activity Functions (GAF) combined into a decision matrix. The second section describes briefly the experts consulted in the validity process. The third section explains the kind of validity test that was given to the experts. Finally, the methodology followed to analyze the results of the validity test is presented.

#### **6.2 Brief Description of Chosen Experts**

Validity of the developed decision model was tested by comparing management actions suggested by the decision model with four greenhouse hydroponic tomato production experts. The following is a brief description about each of the four experts.

##### **Expert #1**

Expert #1 was an active consultant to customers and clients of a commercial hydroponics company. Primary emphasis of the company was to promote and sell technology

and equipment for producing hydroponically grown tomatoes. Once a month, expert #1 taught a weekend intensive, detailed course on hydroponic tomato production using the company's growing systems. He had written a detailed manual for his weekend courses that also served as a reference for his company's experienced growers. He consulted with growers daily by telephone to solve production problems. Expert #1 had a B.S. degree in horticulture and a M.S. degree in vegetable crop production and physiology. He also had training and significance experience in communication skills through both M. Div. degree majoring in theology and public school teaching.

#### **Expert #2**

Expert #2 was an active consultant to over 50 greenhouse tomato and cucumber growers at the time of this research. He had approximately 22 years of research experience on optimizing the production practices for economically growing greenhouse vegetable crops. This included studies of optimum nutrition of greenhouse crops grown in soil, artificial mixes, and hydroponics, diseases and insect control, temperature, humidity, and carbon dioxide control, and post-harvest quality control. Expert #2 had visited greenhouse production areas around the world and was widely known in the industry. Expert #2 had a Ph.D. degree in horticulture science majoring in vegetable crop physiology and had significant experience in a family owned greenhouse floriculture crop production business.

**Expert #3**

Expert #3 was a university instructor of horticultural science with a special emphasis on floricultural crop production in commercial greenhouses. He had 8 years of teaching experience at the undergraduate level and interacted regularly with engineers and plant scientists studying controlled environment plant production related to both vegetable and floriculture crops. Expert #3 also had 2 years of experience with 2 different agricultural businesses where he researched problems related to floriculture crops production and did testing of corn and soybean seeds. Expert #3 studied the tomato plant in his Ph.D. research, but had not maintained any significant contact with the commercial vegetable growers.

**Expert #4**

Expert #4 was an active production manager of a corporate, 12 acre, hydroponic tomato production facility. He had approximately 22 years experience as a grower, consultant, and promoter of controlled environment growing facilities in new remote areas using special energy applications such as co-generation. At the time of this study, he was especially interested in and experimenting with computer controlled fertigation.

Expert # 4 had a B.S. degree in Physics from a Midwestern University and had studied aspects of horticulture and floriculture in continuing education.

**6.3 Priority Test for the Experts**

Twenty-five different input scenarios were generated randomly within the decision model and given to the experts and inputted to the decision model. The five sets



of outputs (four from the experts and one from the decision model) were then analyzed.

The values given to the five variables were generated randomly using the formula:

$$L = L_{\min} + (L_{\max} - L_{\min}) * RN \quad (6.1)$$

where:

$L$  = The calculated random value of one of the five variables: (pH, EC, RT, AT, or RH)

$L_{\min}$  = Minimum value given to one of the five variables: (pH, EC, RT, AT, or RH)

$L_{\max}$  = Maximum value given to one of the five variables: (pH, EC, RT, AT, or RH)

RN = The random number generated inside the software.

The above expression follows from assuming a uniform distribution for each variable between the minimum and the maximum values.

The evaluation of the input scenario by the experts and the model involved two parts. In the first part, the experts were asked to determine whether the value of any of the five variables (pH, electrical conductivity, air temperature, root temperature, or relative humidity) fell within an acceptable range for producing the best quality crop given the specified growing conditions and growth stages.

The second part dealt with the prioritization of the unacceptable variables. The experts were asked to order the unacceptable variables in terms of severity; the value of the variable at the top of the list was the one which, if unchanged, had the highest chance

of producing an inferior crop given the specified growing conditions. Appendix (A) is an example of the input given to the experts.

#### **6.4 Methodology of Analysis and the Scoring of Results**

The validation test results to the 25 scenarios obtained from the experts and the decision model were analyzed statistically. Since there were two parts of the validation test, the analyses were divided into two parts. The first evaluated the matching part; i.e.; the number of interpretations agreed to be acceptable or unacceptable for each variable between each expert and the model. The second evaluated the prioritization part; that is, the agreement between each expert and the model in terms of which variable needed modification first. A score was given for the two parts after analyzing each expert and the corresponding model output. The mathematical constraint for scoring was calculated by the following Equation:

$$\text{Score} = \text{SM1} + \text{SM2} + \text{SP} \quad (6.2)$$

where:

$$\text{Score} \leq 100$$

SM1 = The score for the matching part.

SM2 = Additional matching score for each variable determined to be unacceptable by both the experts and the model (10 in this analysis).

SP = The score for the prioritization part (28 in this analysis).

X = (100 - maximum for SP), (72 in this analysis)

$$\text{SM1} + \text{SM2} \leq X$$

The following is an explanation of the analysis procedure that was developed together with the statistics lab at the Ohio Agricultural Research and Development Center (OARDC):

1. The score for the matching part, when the expert and the model agreed, was assigned using weighting factors dependent upon the number of matches between the expert and the model. Since in this analysis five variables were considered, the number of matches were: 0, 1, 2, 3, 4, or 5. Based on this condition, three mathematical steps were then carried out in order to assign a score corresponding to each number of matches.

i) Weighting factors were computed for each case by assigning a number from  $2^0$  to  $2^{n-1}$ , where (n) is the number of variables being interpreted by the expert and the model (five in this analysis). For the case  $n = 5$  the assigned numbers were 1, 2, 4, 8, and 16 and the sum of the assigned numbers is 31.

ii) If the total score assigned for the matching part were (X), this (X) was proportioned among the matches between the experts and the decision model using:  $(X*1/31)$ ,  $(X*2/31)$ ,  $(X*4/31)$ ,  $(X*8/31)$ , and  $(X*16/31)$ . In this study (X) was given a value of 72.

iii) The score for the case of five matches was the sum of all the weights, which was basically the value (X). The score for four matches was determined by subtracting the highest weight  $(X*16/31)$ . The score for three matches was determined by

subtracting the second highest weight to make the total number subtracted  $(X*8/31)$  plus  $(X*16/31)$ . The same calculations were carried out until the case of zero matches in which a zero score was given.

2. The score of the matching part was given an additional score (Y) for each variable determined to be unacceptable by both the expert and the model. However, there was one condition that the total score of matching  $(SM1 + SM2)$  could not exceed the value (X) such that the total score of matching did not exceed the assigned value (X). In this study (Y) was given a value of 10.

3. The score for the prioritization part was assigned based upon how closely the determinations of the model and the expert agreed in terms of which variables needed to be modified first. The computations of this score was carried out in three steps:

i) The first number used to determine this score was (j). Where (j) was the number of comparisons among the five variables specified by the expert. (j) was calculated by the following equation:

$$j = \sum_{k=1}^m (n-k) \quad (6.3)$$

where:

n = The number of variables interpreted by the expert and the model (five in this analysis).

m = The number of variables determined by the experts which require adjustments.

Thus for  $m = 0, 1, 2, 3, 4, \text{ or } 5$  then  $j = 0, 4, 7, 9, 10$  or  $10$ , respectively.

ii) The second number used to determine the ordering score was (c), where (c) was the number of ordered comparisons correctly determined by the model.

iii) The formula used then to compute the score for the ordering part was

$$c \times (100 - X) / j. \quad (6.4)$$

(c) was evaluated by comparing the model chosen sequence of variables with the expert sequence of variables and counting the number of correct orderings.

The total score resulted from an analysis of each output scenario, and represented how closely the determinations of the model were to those of the experts in terms of both matching and prioritization.

Finally, after conducting the analysis and calculating the score for each output, a statistical analysis was carried out that included the arithmetic mean of all the scores for the twenty five output scenarios, the standard deviation, and a 95% confidence interval (CI) for the mean. The CI formula used was:

$$\bar{x} \pm (t \text{ critical value}) \times s / \sqrt{n} \quad (6.5)$$

where:

$\bar{x}$  = The arithmetic mean of all the scores.

s = The standard deviation

n = The total number of runs (25 in this analysis).

A computer program was written to carry out the above analysis as well as the statistical analysis.

## **CHAPTER VII**

### **RESULTS AND DISCUSSION**

#### **7.1 Introduction**

This chapter shows the results of the decision model (HYTODMOD) validity test and the statistical analysis conducted on the results of the test. Also, a sensitivity analysis on the scoring weight was done.

#### **7.2 Validity of Test Results**

As explained in the last chapter, following the development of the HYdroponic TOMato Decision MODEL (HYTODMOD), a validity test was carried out with experts. Appendix (A) shows an example of the 25 input scenarios given to the four experts.

The results of the validation test was divided into two parts. The first part analyzed the degree of matching between the expert and the model outputs; that is the number of times the experts and the model agreed on the acceptability of the five tested variables. The second part involved the statistical analysis of the validity of the model in terms of both the matching and the prioritization parts.

### **7.2.1 Matching Results with Experts**

The number of times each expert agreed with the other as well as with the decision model for each of the five tested variables out of the twenty five times was counted and recorded in Table 7.1. After receiving the data from the four experts, experts #1, and #3 were interviewed to discuss some of the differences between their output and that of the decision model. Discussion for each key test result is presented in the next section.

Table 7.1 Number of Matching Agreements among Four Greenhouse Tomato Production Experts, and Between the HYTODMOD Model and the Experts Based on 25 Input Scenarios.

Test	E1 & E2		E1 & E3		E1 & E4		E1 & M		E2 & E3		E2 & E4		E2 & M	
	before	after	before	after	before	after	before	after	before	after	before	after	before	after
RT	21	21	16	15	23	21	12	11						
EC	15	16	18	17	22	24	21	21						
pH	19	22	21	22	22	19	17	19						
AT	19	18	15	15	18	16	9	9						
RH	18	16	13	15	16	19	10	12						

Test	E3 & E4		E3 & M		E4 & M		M & (E1, E2, E3, E4)		M & (E1, E3, E4)	
	before	after	before	after	before	after	before	after	before	after
RT	16	15	21	22	10/11	10/11	20/21			
EC	20	20	21	23	14/15	17/17	18/18			
pH	22	25	25	22	16/16	16/16	20/20			
AT	18	18	19	25	9/9	9/9	16/16			
RH	16	16	20	24	6/7	7/8	14/15			

RT : Root temperature.  
 EC : Electrical conductivity of feeding solution.  
 pH : pH of feeding solution.  
 AT : Air temperature.  
 RH : Relative humidity.  
 E1, E2, E3, & E4 : Experts #1, #2, #3, & #4 respectively.  
 E(#) & E(#) : Number of times both experts agreed.  
 E(#) & M : E(#) & M : Number of times expert (#) & the model agreed.  
 Before : Before interviewing with the expert.  
 After : After interviewing with the expert.  
 M & (E1, E2, E3, E4) : Number of times the model agreed with the 4 experts out of their total number of agreements.  
 M & (E1, E3, E4) : Number of times model agreed with experts 1, 3, & 4 out of their total number of agreements.



### **7.2.1.1 Hydrogen Ion Concentration of the Feeding Solution**

- Table 7.1 shows for the Hydrogen Ion Concentration (pH), the Hydroponic Tomato Decision Model (HYTODMOD) output was closest to expert #3's output, agreeing 25 out of 25 times.
- HYTODMOD agreed with expert #4 22 out of 25 times. Expert #4 considered pH of 5.7, 5.8, and 6.5 as unacceptable while HYTODMOD did not. HYTODMOD agreed with expert #1 22 of 25 times. The differences occurred due to the fact that expert #1 considered a pH of 5.0 and 5.2 as acceptable while HYTODMOD did not. Also, this expert considered a pH of 6.5 as unacceptable while HYTODMOD did not.
- The output results of expert #2 indicated that the meaning of acceptability was not clearly explained to him. While an acceptable range for the current study can produce the best quality crop based on the given growing conditions, he considered any value as an acceptable one unless extremely low or high. This misunderstanding was also evident with the rest of the variables: EC, RT, AT, and RH. Due to this fact expert #2 was excluded from the analysis of the rest of the variables.
- The last column of Table 7.1 shows that of the 20 times experts #1, #3, and #4 agreed, HYTODMOD output matched their outputs all 20 times.

### **7.2.1.2 Root Temperature**

- Table 7.1 shows for the root temperature (RT), the HYTODMOD output agreed most closely with expert #1 (23 out of the 25 times after the interview), followed by expert #4 (22 out of the 25 times), and finally by expert #3 (21 out of the 25 times).
- Expert #3 considered a RT of 27.3 and 27.5°C acceptable, while HYTODMOD did not. However, HYTODMOD gave these temperatures a utility of 0.94 and 0.95 respectively, which is quite close to the acceptable range.
- Expert #4 considered a RT of 25.6°C for the stages of germination and early growth and the seedling stages on a cloudy day as unacceptable, while experts #1 and #2, and HYTODMOD considered it acceptable.
- Based on the output results of experts' #1, #3, #4 and the discussion with experts #1 and #3, the lower bound of HYTODMOD optimum range for the germination and early growth and the seedling stages was changed from 25°C to 23°C as shown in Figure 7.1. Also, the upper bound of HYTODMOD optimum range for the vegetative to the termination stages was changed from 22.2°C to 24°C as shown in Figure 7.2.
- The last column of Table 7.1 shows that of the 21 times that experts #1, #3, and #4 agreed, HYTODMOD output matched the experts' outputs 20 times.

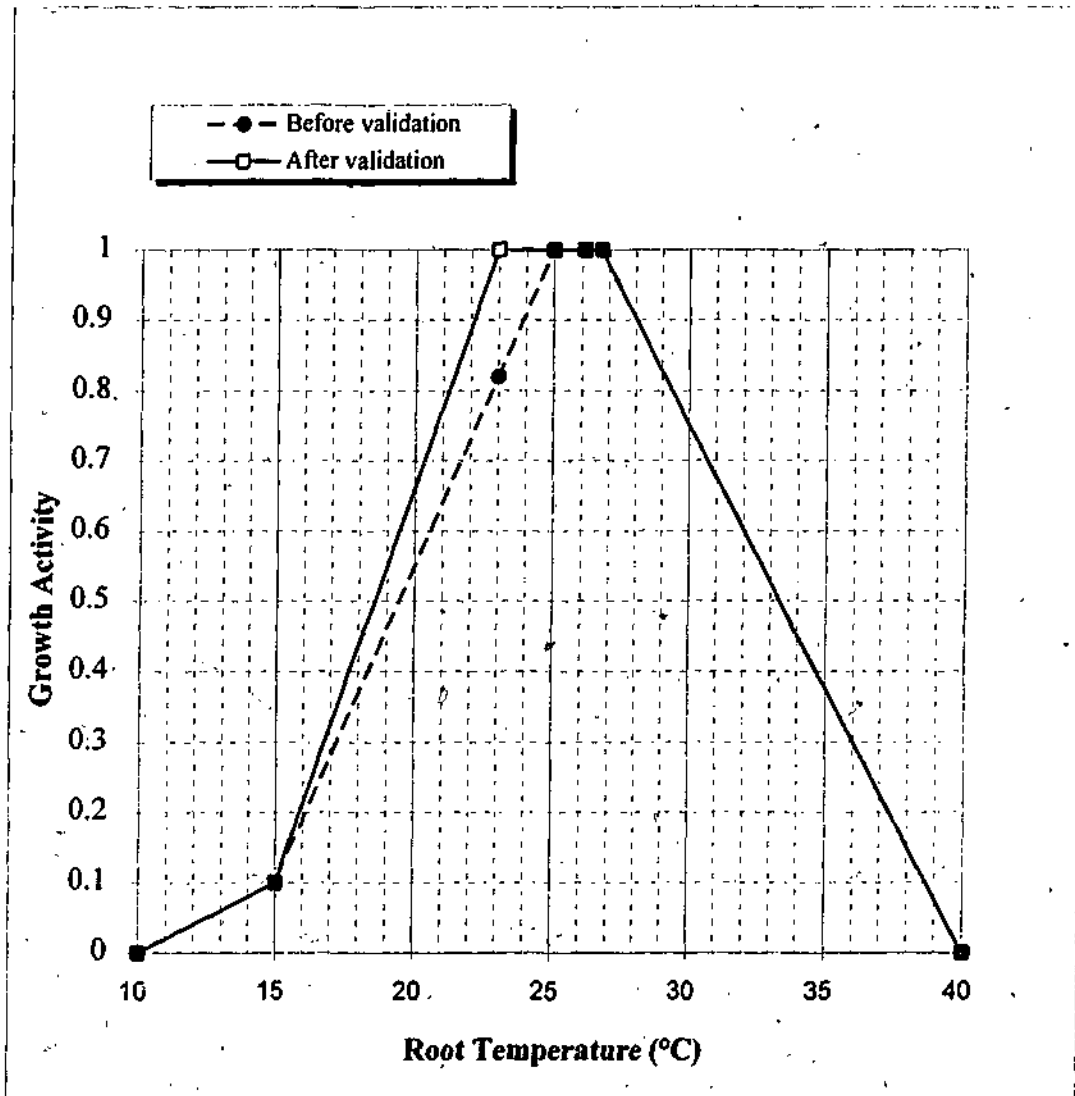


Figure 7.1 Tomato Growth Activity Function for Root Temperature from Germination and Early Growth Stage until Seedling Stage for Producing Best Crop before and after Validation.

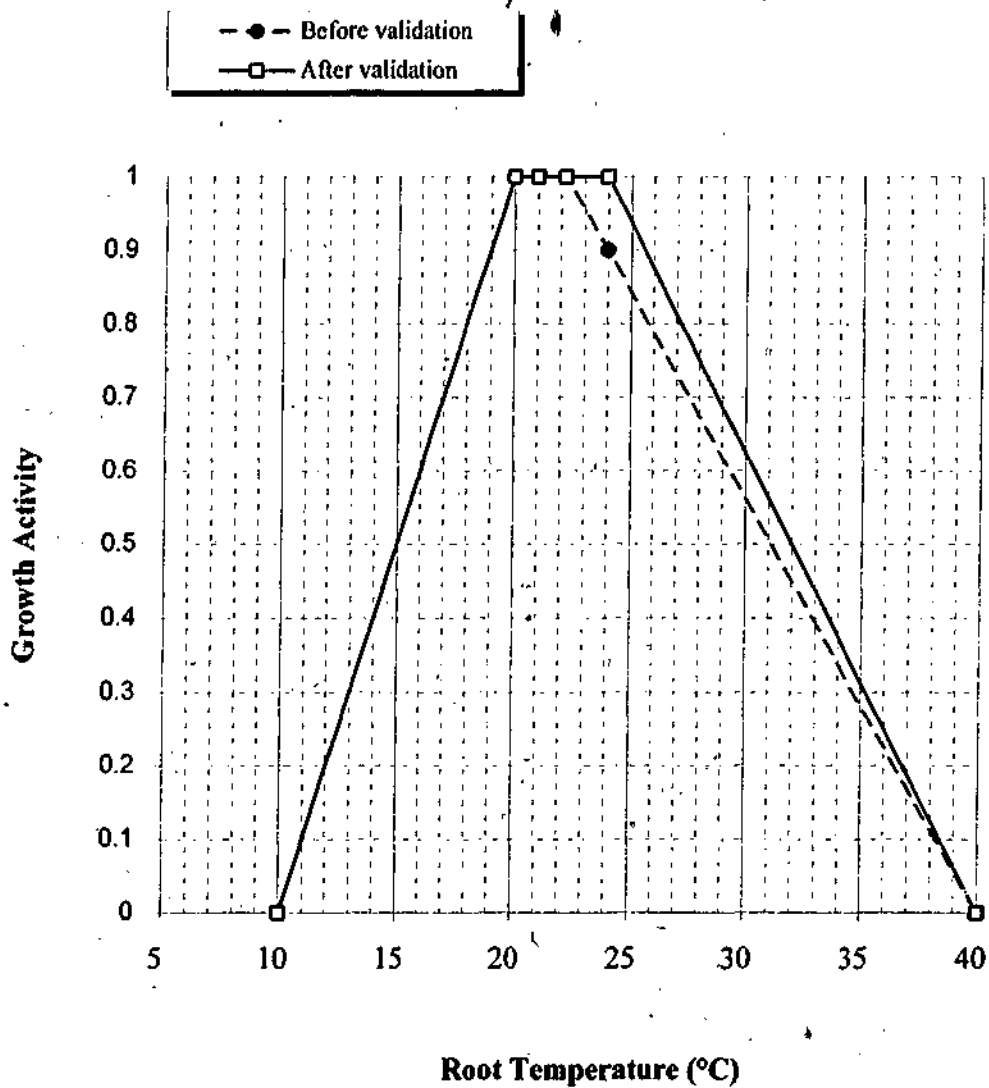


Figure 7.2 Tomato Growth Activity Function for Root Temperature from Vegetative Stage until Termination Stage for Producing Best Crop before and after Validation.

### 7.2.1.3 Air Temperature

- Table 7.1 shows that for the air temperature (AT), the HYTODMOD output agreed most closely with expert #4 (25 out of 25 times), followed by expert #3 (19 out of the 25 times after the interview), and finally by expert #1 (18 out of the 25 times after the interview).
- Expert #1 considered AT of 17.3°C in both the early fruiting stage at night, and the vegetative stage at night as acceptable, while experts #3 and #4, and HYTODMOD considered it unacceptable. Also, expert #1 considered an AT of 17.5°C for a mature fruiting stage on a sunny day as acceptable, while experts #3 and #4, and HYTODMOD did not.
- Experts #1 and #3 considered an AT of 21.9°C in the seedling stage on a sunny day as acceptable, while expert #4 and HYTODMOD did not.
- Expert #3 respectively considered AT's of 29.2 and 27.1°C in the germination and early growth stages on a cloudy day, and in the seedling stage on a cloudy day as acceptable, while experts #1 and #4, and HYTODMOD considered those AT's unacceptable.
- Based on the output results and discussion with experts #1, and #3, the HYTODMOD optimum range for the stages from seedling to termination on a sunny day was changed from (22.8 - 25.6°C to (24 - 26.7°C as shown in Figure 7.3. Also, HYTODMOD optimum range for the stages from seedling until termination stages on a cloudy day was changed from (20 - 23.3°C to (22 - 24°C as shown in Figure 7.4.

- The last column of Table 7.1 shows that of the 16 times that experts #1, #3, and #4 agreed, HYTODMOD output matched the experts choices all 16 times.

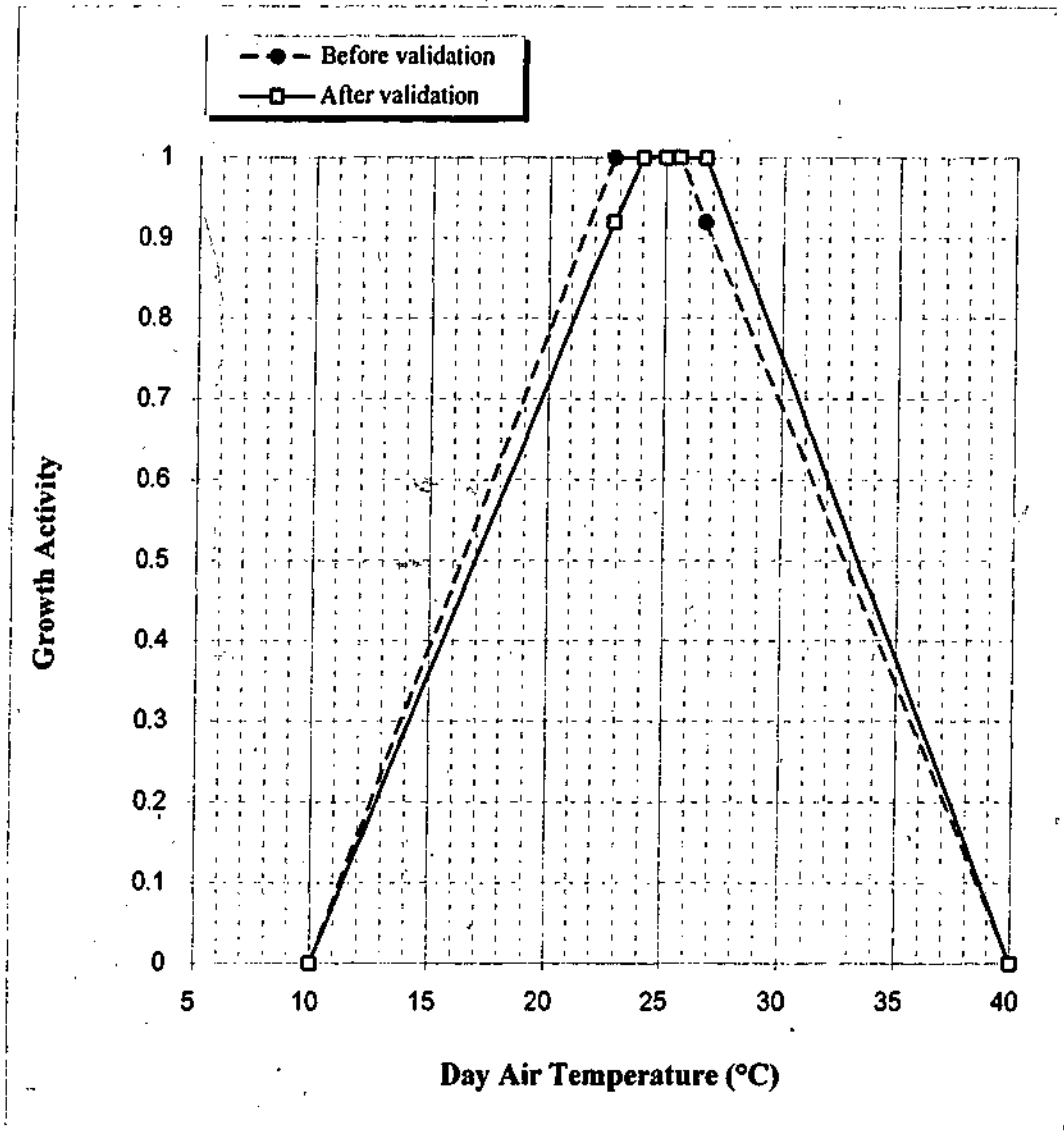


Figure 7.3 Tomato Growth Activity Function for Sunny Day Greenhouse Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop before and after Validation.

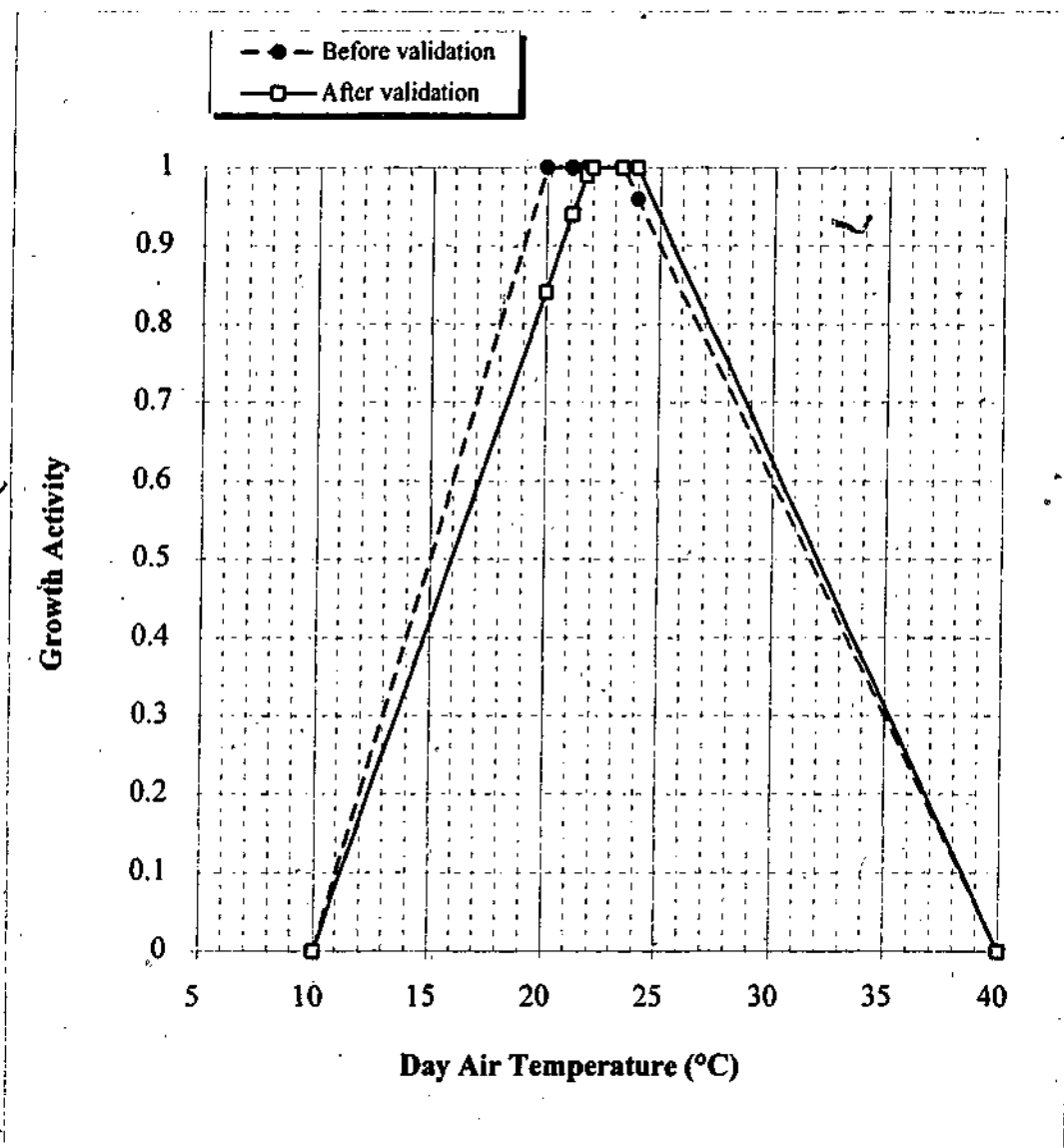


Figure 7.4 Tomato Growth Activity function for Cloudy Day Greenhouse Air Temperature from Seedling Stage until Termination Stage for Producing Best Crop before and after Validation.

#### **7.2.1.4 Electrical Conductivity of the Feeding Solution**

- Table 7.1 shows that for the electrical conductivity (EC), the HYTODMOD output agreed most closely with expert #4 (23 out of the 25 times), followed by expert #1, (22 out of 25 times after the interview), and finally with expert #3 (21 out of the 25 times after the interview).
- Expert #3 considered an EC of 1500  $\mu\text{mhos/cm}$  in the mature fruiting stage at night as acceptable, while experts #1 and #4, and HYTODMOD, considered it unacceptable. Under the same conditions, expert #1 considered an EC of 3100  $\mu\text{mhos/cm}$  as acceptable, while experts #3 and #4, and HYTODMOD, considered it unacceptable.
- Expert #3 considered an EC of 3500  $\mu\text{mhos/cm}$  in mature fruiting stage on a cloudy day to be unacceptable, while experts #1 and #4, and HYTODMOD, considered it acceptable.
- Expert #3 considered an EC of 1900  $\mu\text{mhos/cm}$  in the vegetative stage at night to be acceptable, while experts #1 and #4, and HYTODMOD, considered it unacceptable.
- Experts #3 and #4 considered an EC of 1700  $\mu\text{mhos/cm}$  in the seedling stage on a cloudy day to be acceptable, while expert #1, and HYTODMOD, considered it unacceptable.
- Based on the output results of experts #1, #3 and #4 and the discussion with experts #1, and #3, HYTODMOD optimum range for the seedling to termination stages on a sunny day was modified from (2300 - 2500  $\mu\text{mhos/cm}$ ) to (2300 - 2800  $\mu\text{mhos/cm}$ )



as shown in Figure 7.5. Also, HYTODMOD optimum range for the seedling to termination stages on a cloudy day was modified to (3100 - 4000  $\mu$ mhos/cm) as shown in Figure 7.6.

- The last column of Table 7.1 shows that of the 18 times that experts #1, #3, and #4 agreed, HYTODMOD output matched the experts 18 times.

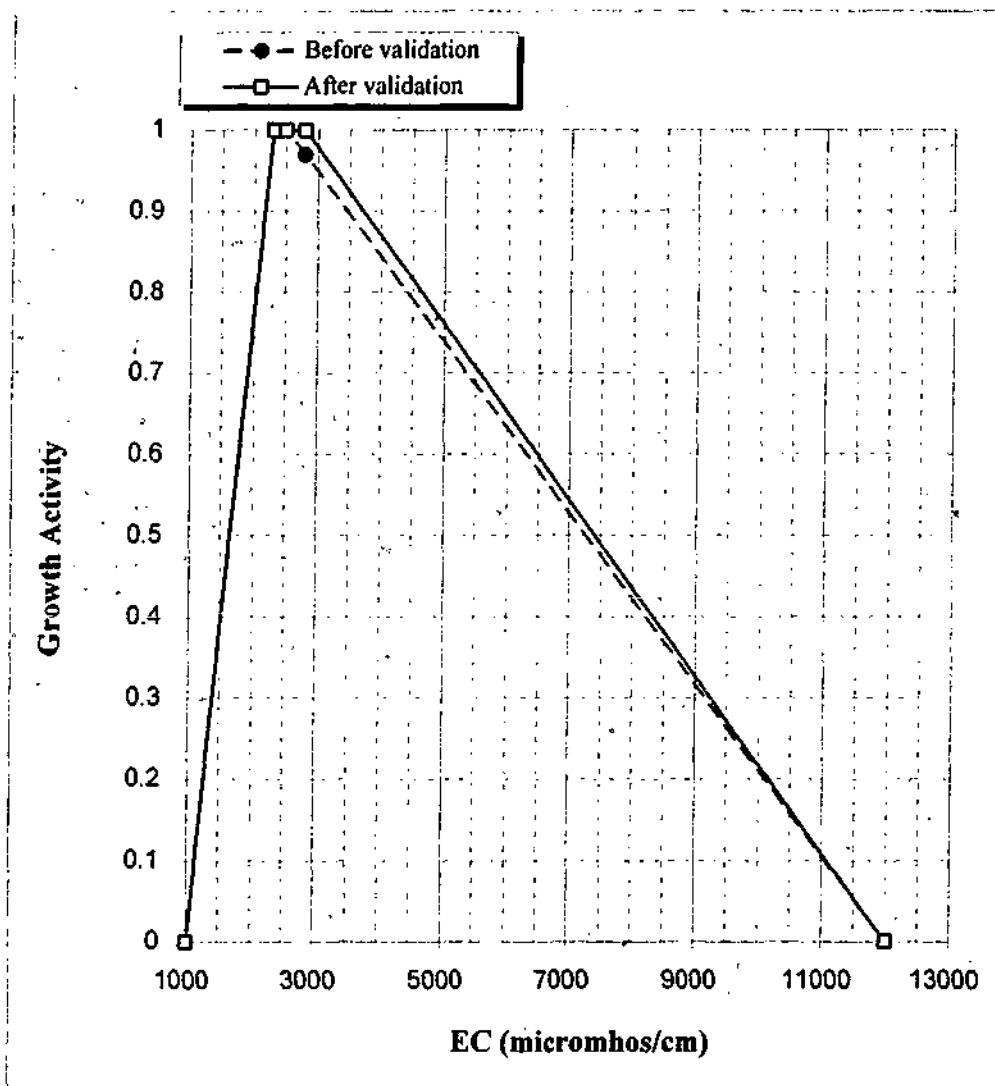


Figure 7.5 Tomato Growth Activity Function for Sunny Day Feeding Solution Electrical Conductivity from Seedling Stage until Termination Stage for Producing Best Crop before and after Validation.

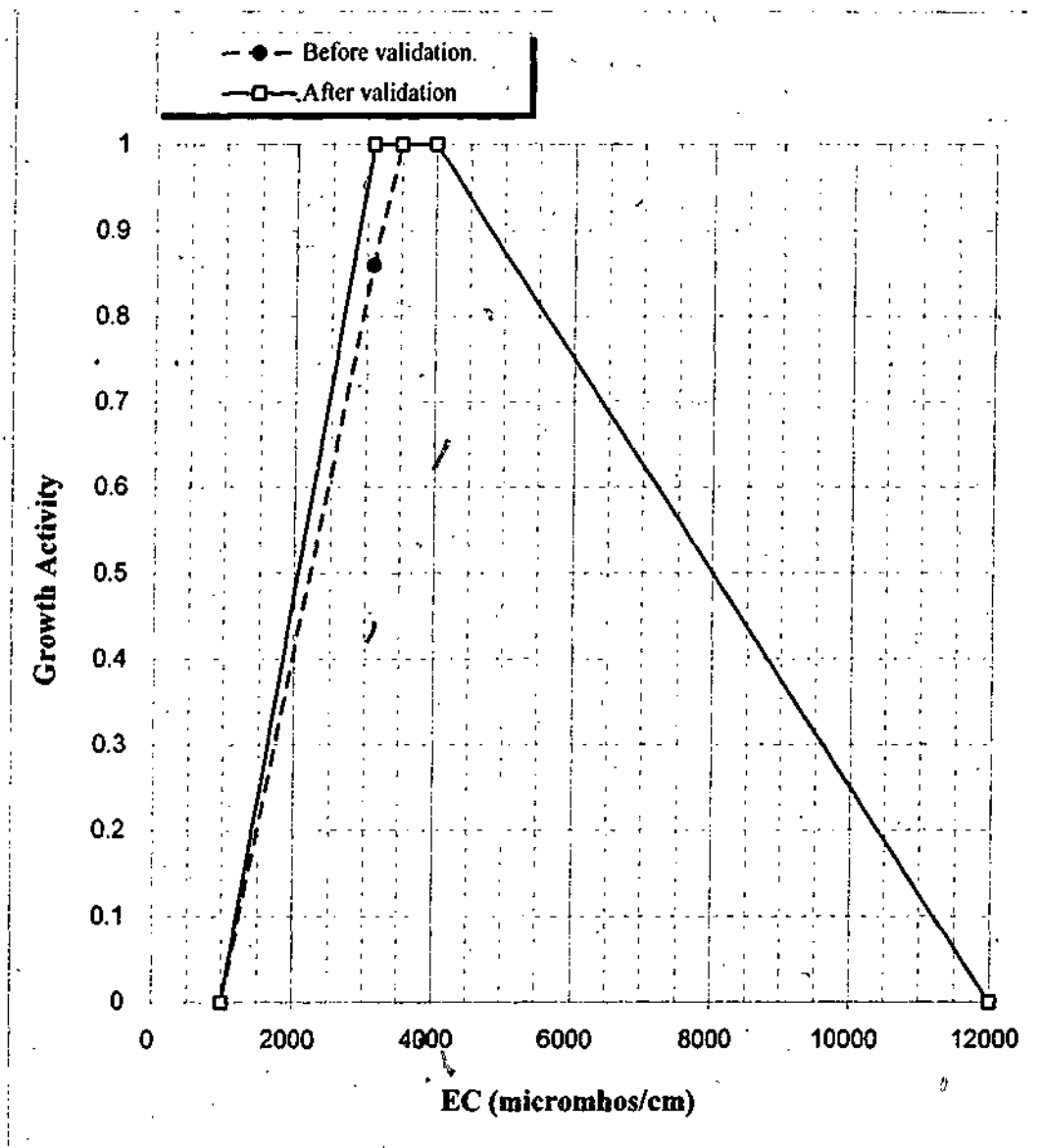


Figure 7.6 Tomato Growth Activity Function for Cloudy Day Feeding Solution Electrical Conductivity from Seedling Stage until Termination Stage for Producing Best Crop before and after Validation.

### **7.2.1.5 Relative Humidity**

- Table 7.1 shows for the relative humidity, the HYTODMOD output agreed most closely with expert #4's output (24 out of the 25 times), followed by expert #3 (20 out of the 25 times after the interview), and finally with expert #1 (16 out of the 25 times after the interview).
- Expert #1 considered a RH of 60, and 61% in the germination and early growth stages at night and on a sunny day acceptable, while experts #3 and #4, and HYTODMOD did not.
- Experts #1 and #3 considered a RH of 67% in the seedling stage on a cloudy day acceptable, while expert #4 and HYTODMOD did not.
- Experts #1, #3, and #4 considered a RH of 68% in the seedling stage on a sunny day acceptable, while HYTODMOD did not.
- Expert #1 considered a RH of 55% and 56% in the seedling stage on a sunny day acceptable, while experts #3 and #4, and HYTODMOD did not. Also, expert #1 considered an RH of 56% for a mature fruiting stage on a sunny day acceptable, while experts #3 and #4, and HYTODMOD did not.
- Based on the output results of experts #1, #3 and #4 and the discussion with experts #1 and #3, HYTODMOD utility for an RH of 100% during the germination and early growth stage was changed to (1) from (0.6) as shown in Figure 7.7. Also, the lower bound of HYTODMOD optimum range for the seedling stage was changed to 70% from 75% as shown in Figure 7.8.

The last column of Table 7.1 shows that of the 15 times that experts #1, #3, and #4 agreed, HYTODMOD output matched the experts' outputs 14 times.

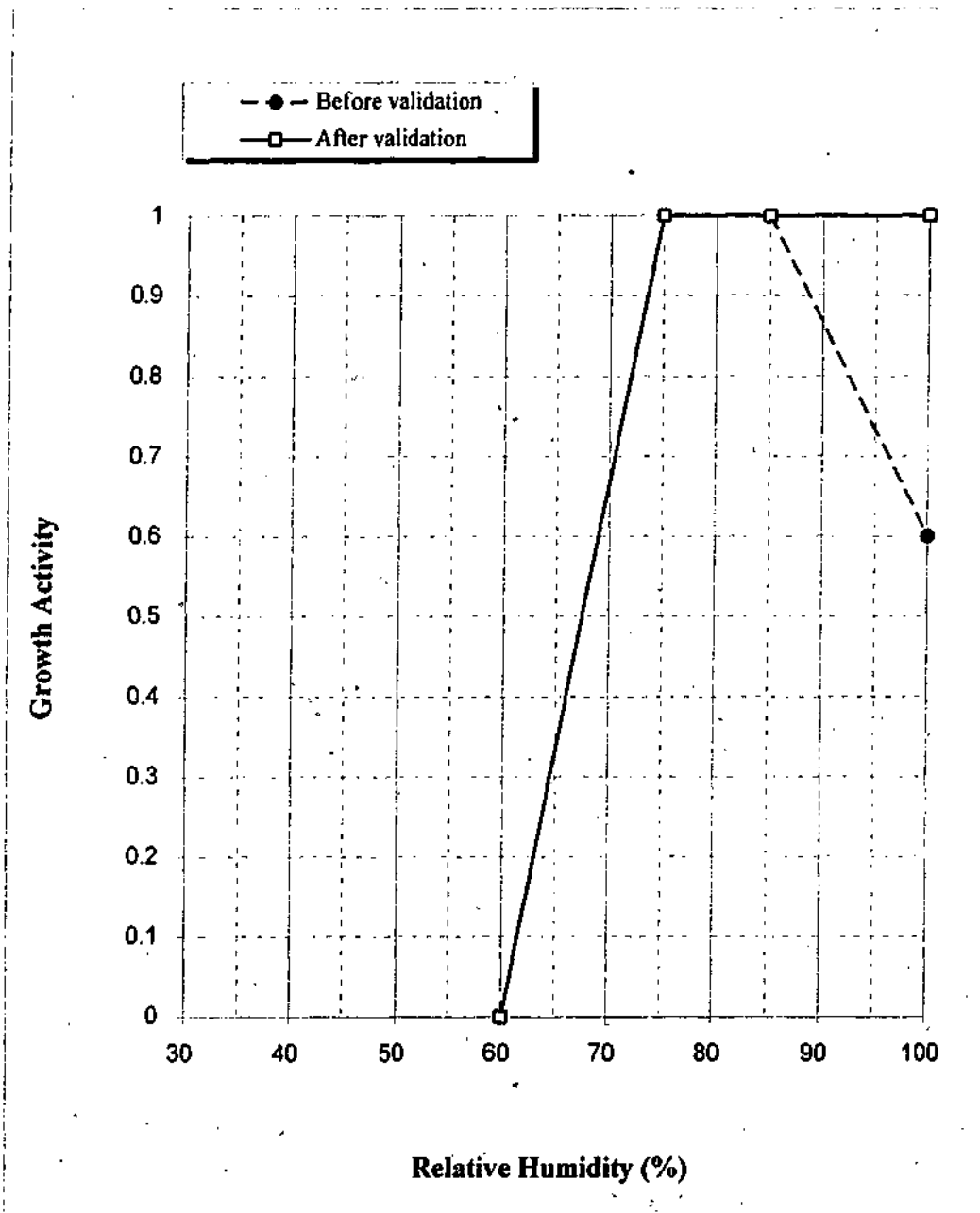


Figure 7.7 Tomato Growth Activity Function for Greenhouse Air Relative Humidity during Germination and Early Growth Stage for Producing Best Crop before and after Validation.

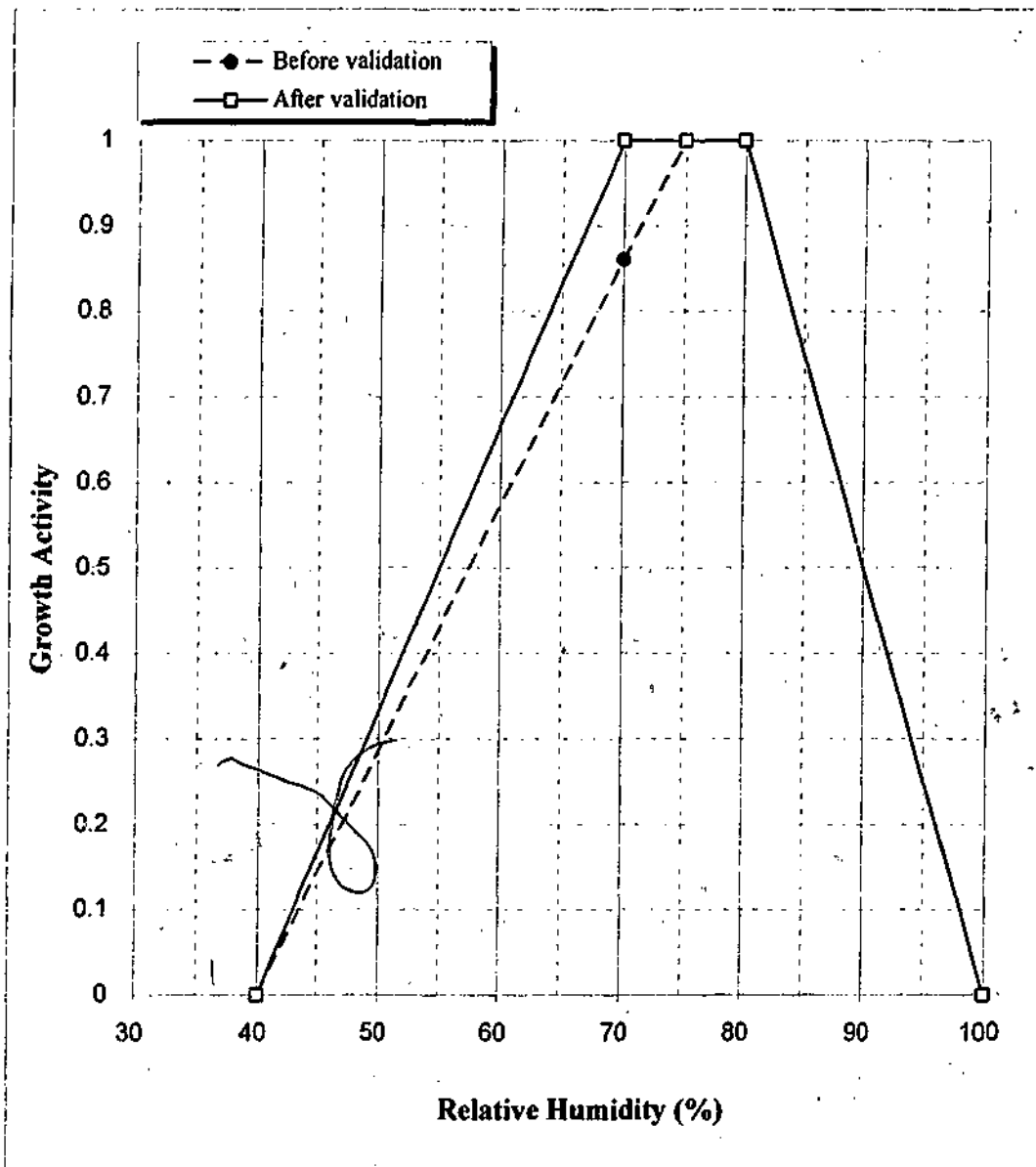


Figure 7.8

Tomato Growth Activity Function for Greenhouse Air Relative Humidity during Seedling Stage for Producing Best Crop before and after Validation.

### 7.2.2 Sensitivity Analysis on Scoring Weights

Prior to scoring the recommendations between the model and each expert, a sensitivity analysis was done to measure the validity of such a score. As was mentioned in section 6.4, one score was given for the matching section and another for the prioritization section. More variation was expected between the experts and HYTODMOD in prioritization matching; therefore, a higher share of the total score was given for the matching part. The initial estimate was a score of 72 for the matching part and 28 for the prioritization part.

The output results of expert #3 were used for the sensitivity analysis process. Table 7.2 shows the results of the arithmetic mean, and the lower and upper bounds of the 95% confidence interval corresponding to the scores: 60, 65, 70, 72, 75, and 80.

Table 7.2 Sensitivity Analysis on Scoring Weights

	A. M.	L. B. of CI	U. B. of CI
Score			
60	84.6	79.0	90.1
65	84.9	79.1	90.7
70	85.5	79.4	91.6
72	85.7	79.4	91.9
75	85.8	79.3	92.3
80	86.2	79.4	93.0

A. M. = Arithmetic mean.

L. B. of CI = The lower bound of 95% confidence interval.

U. B. of CI = The upper bound of 95% confidence interval.

As shown in Table 7.2, the variation in the arithmetic mean was 1.6; the lower bound was 0.4; and the upper bound was 2.9. This analysis showed that a score of 72 is a good estimate. The variation in the arithmetic mean and the lower bound of the 95% CI was small. If the score corresponding to the highest upper bound (80) was picked, it would have been on account of the prioritization share of the score that could have been 20.

### **7.2.3 The Statistical Analysis Results**

The procedures used in the statistical analysis were explained in chapter 6. A score of 100 was given to a complete matching and exact prioritization between each expert and the HYTODMOD. The share of the matching part was 72, referred to as (X) in the last chapter, while the share for the prioritization part was 28. Tables 7.3 shows the statistical analysis results for experts 1, 2, 3, and 4.

The highest score achieved was between expert #4 and the HYTODMOD, as shown in Table 7.3, the arithmetic mean and the 95% CI were 88, and 83-92 respectively. Then next highest score achieved was between expert #3 and the HYTODMOD, with an arithmetic mean and 95% CI of 85 and 79-91 respectively. Next came the score achieved from the statistical analysis of expert #1 and the HYTODMOD outputs, with an arithmetic mean and 95% CI of 80 and 75-86 respectively. Finally, came the score achieved from the statistical analysis of expert #2 and the HYTODMOD outputs with arithmetic mean and 95% CI of 60 and 52-68.5 respectively.



Table 7.3 Statistical Analysis on the Compatibility of the Decision Model (HYTODMOD) Output with Each of the Four Expert Outputs.

<i>Output set#</i>	<i>Expert #1 Score</i>	<i>Expert #2 Score</i>	<i>Expert #3 Score</i>	<i>Expert #4 Score</i>
1	91.6	91.6	94.4	91.6
2	91.6	55.0	97.2	94.4
3	93.8	96.9	100.0	65.6
4	51.0	64.7	94.4	97.2
5	45.3	40.0	75.0	54.7
6	80.4	64.7	74.8	80.4
7	83.7	45.0	89.9	91.6
8	67.8	74.0	100.0	91.6
9	80.6	38.0	97.2	91.6
10	80.4	43.0	83.2	91.6
11	93.8	54.7	87.4	84.6
12	67.8	35.0	91.6	97.2
13	88.8	31.0	77.4	86.0
14	83.7	52.0	83.7	83.7
15	94.4	58.4	88.8	91.6
16	80.4	77.6	83.2	100.0
17	94.4	86.8	89.9	97.2
18	61.6	55.0	91.6	91.6
19	86.0	64.7	86.0	91.6
20	86.0	43.0	91.6	86.0
21	70.9	55.0	51.0	100.0
22	93.0	86.8	97.2	94.4
23	70.9	97.2	91.6	91.6
24	83.2	61.6	91.6	88.8
25	88.8	33.0	33.0	67.8

**Table 7.3 (continued) Statistical Analysis on the Compatibility of the Decision Model (HYTODMOD) Output with Each of the Four Expert Outputs.**

Sum of the scores	2009.9	1504.7	2141.7	2202.344
A.M.of the scores	80.4	60.2	85.7	88.1
STD. DEV. of the scores	13.5	20.2	15.1	10.9
L. B. of the 95% CI	74.9	51.9	79.4	83.6
U. B. of the 95% CI	85.9	68.5	91.9	92.6
L. B. of the 90% CI	75.8	53.3	80.6	84.4
U. B. of the 90% CI	85.0	67.1	90.8	91.8

A.M= Arithmetic mean

L.B.= Lower Bound

U.B.= Upper Bound

STD. DEV.= Standard Deviation

The key reasons for the arithmetic mean and the 95 % CI statistics were as follows:

1. There were matching differences of opinion that were discussed in the previous section.
2. When prioritizing, expert #1 decided most of the time to deal first with the variables having a short-term effect on the plant (such as pH or EC) before the ones that could have a long term effect, such as RH. He believed that the short-term effect could lead to damage very quickly if not corrected immediately.
3. Expert #1 considered a pH of above 7.0 very likely to produce a poor quality crop in all stages, while the HYTODMOD considered it possible to have a pH as high as 10. This difference significantly affected the ordering of expert #1 and HYTODMOD for the pH among the other variables.
4. Expert #1 considered RT and AT above 29.4°C for all stages to be very likely to produce a poor quality crop. However, the HYTODMOD and expert #3 considered the worst effect to occur at a temperature of 40°C. This difference affected the ordering of experts #1 and #3 and HYTODMOD for the temperatures among the other variables.
5. Expert #3 considered an EC above 2000  $\mu\text{mhos/cm}$  at the germination stage on a cloudy day to be very likely to produce a poor quality crop. However, HYTODMOD and expert #1 considered this level to be the optimum to produce the best quality crop. Also, expert #3 considered an EC above 4000  $\mu\text{mhos/cm}$  for the stages from

vegetative until termination at night or on a cloudy day to be the worst for producing a high quality crop. However, HYTODMOD and expert #1 considered this level to be the optimum for producing the best quality crop for the above mentioned growing conditions.

6. The HYTODMOD considered the worst level of EC for both the germination stage and seedling through termination stages on a sunny day to start at 5000 and 12000  $\mu\text{mhos/cm}$  respectively. However, experts #1 and #3 considered the worst level under the same growing conditions to start at a level above 5100  $\mu\text{mhos/cm}$ . The above two differences affected the ordering of experts #1 and #3 and HYTODMOD for the EC among the other variables.
7. Expert #3 considered a RH range of 60-70% for the germination and early growth stages on either a cloudy day or at night to be the best, while HYTODMOD considered this range to be poor for the germination and early growth stage. Also, the expert considered a RH above 80 % for the stages from vegetative until termination on a sunny day to be poor, while the same RH was considered the best under the same growing conditions by HYTODMOD.

## CHAPTER VIII

### CONCLUSIONS

The general objective of this study was to develop an integrated decision model for a hydroponic tomato grower that would prioritize the necessary actions based upon the probability of producing high yield, high quality fruit.

The following conclusions can be drawn from this study:

- 1) Five key tests were identified to be necessary for the production of high yield, high quality hydroponic tomato fruits. These five tests were:
  - i) The pH of the feeding solution.
  - ii) The electrical conductivity of the feeding solution.
  - iii) The air temperature inside the greenhouse.
  - iv) The root temperature.
  - v) The relative humidity.
- 2) Growing optimum ranges for each of the five key tests were identified for five growing stages of a hydroponically grown tomato crop. The growth stages were:
  - i) The germination and early growth stage.
  - ii) The seedling stage.
  - iii) The vegetative stage.
  - iv) The early fruiting stage.

v) The mature fruiting stage.

- 3) A computer decision model called HYdroponic TOMato Decision MODel (HYTODMOD) was developed that carried out specific objectives 1 - 4.
- 4) Actions related to key tests could be prioritized by a HYTODMOD model with a high level of agreement with four different experts.
- 5) Growth Activity Functions (GAFs) could be used to describe the potential influence of various levels of five key tests on the production of a greenhouse tomato crop.
- 6) An adjustment subroutine of a decision model could be used as a help function to identify necessary actions needed to correct the unacceptable test result.
- 7) Successful hydroponic tomato production is highly dependent on at least five tests that must be done accurately.
- 8) The decision model was validated by comparing the model recommendations with the experts recommendations using a randomized test of growing conditions. The statistical variation which occurred among the experts confirmed the opportunity for an integrated decision model that can provide hydroponic tomato growers with the necessary expertise to produce a high quality crop.

**CHAPTER IX**  
**RECOMMENDATIONS FOR**  
**FUTURE RESEARCH**

Based on this study, the following improvements to the HYdroponic TOMato Decision MODel (HYTODMOD) software, and future research are recommended:

1. The nutrient composition of the feeding solution should be added as a key test. The optimum level of each of the macro- and micro-nutrients for the different growing stages need to be determined accurately.
2. The moisture content of the growing media should be added as a key test. The optimum levels at various different times of the day for the different growing stages need to be identified. This will prevent any over irrigation that would lead to an excessive waste of nutrient.
3. The list of actions included in the HYTODMOD model should be modified to include more detailed actions that can suit various specific growing conditions.
4. The frequency of conducting each key test should be determined.
5. The germination and early growth stages should be separated into two stages with separate subroutines for each stage.

6. The HYTODMOD model should be interfaced with an automatic control greenhouse software.
7. The user friendliness interaction between the model and the grower should be tested and improved.
8. The HYTODMOD should be considered for other crops after making any necessary changes to the model.
9. The diagnostic and growth models should be incorporated to the HYTODMOD.



## LIST OF REFERENCES

Abdalla, and K. Verkerk. 1968. Growth, flowering, and fruit-set of the tomato at high temperature. *Netherlands Journal of Agriculture Science* 16:71-76

Abdelhafeez, A. T. and K. Verkerk. 1969. Effects of temperature and water-regime on the emergence and yield of tomatoes. *Netherlands Journal of Agriculture Science* 17:50-59

Abdelhafeez, A.T., H. Harssema, G. Veri and K. Verkerk. 1971. Effect of soil and air temperature on growth, development and water use of tomatoes. *Netherlands Journal of Agriculture Science* 19:67-75

Abu Hadid, A. F. 1991. Ventilation, Cooling, and Heating in the plastic greenhouses. Technical publication #1.

Adams, P. 1991. Effects of increasing the salinity of the nutrient solution with major nutrient or sodium chloride on the yield, quantity and composition of tomatoes grown in rockwool. *Journal of Horticultural Science* 66 (2):201-207

Adams; P. 1991. Effect of diurnal fluctuations in humidity on the accumulation of nutrients in the leaves of tomato (*Lycopersicon esculentum*). *Journal of Horticultural Science* 66(5):545-550

Adams, P. and R. Holder. 1992. Effects of humidity, Ca and salinity on the accumulation of dry matter and Ca by the leaves and fruit of tomato (*Lycopersicon esculentum*). *Journal of Horticultural Science* 67(1):137-142

Al-Shooshan, A. A., 1991. Greenhouse total water use analysis modeling and optimization. Ph. D. Dissertation. The Ohio State University, Columbus, OH.

Anderson, J. R., J. L. Dillon, and J. B. Hardaker. 1977. *Agricultural Decision Analysis*. The Iowa State University Press.

- Armstrong, M. J. and E. A. Kirkby. 1979. The influence of humidity on the mineral composition of tomato plants with special reference to calcium distribution. *Plant and soil* 52:427-435
- Avissar, R. and Y. Mahrer. 1982. Verification study of a numerical greenhouse microclimate model. *Transactions of ASAE*, p. 1711.
- Bakker, J. C. 1990. Effects of day and night humidity on yield and fruit quality of glasshouse tomatoes (*Lycopersicon esculentum* Mill). *Journal of Horticultural Science* 65(3):323-331
- Banuelos, G. S., G. P. Offermann and E. C. Seim. 1985. High relative humidity promotes blossom end rot (BER) on growing tomato fruit. *HortScience* 20(5):894-895
- Beer, K. and H. Ansoorge. 1989. System of computer-aided fertilizer recommendations (DS 87) in field vegetable production in the GDR. *Act Hort* 260:181
- Biemond, T. 1989. A tomato growth model as part of a bio-economical model. *Acta Horticulturae*. (260):285
- Bogmann, B. 1983. A bio-economic simulation model for short-term planning and control in greenhouse production. *Acta Horticulturae*.135, p. 63-71
- Bradfield, E.G. and C.G. Guttridge. 1984. Effects of night time humidity and nutrient solution concentration on the calcium content of Tomato. *Scientia Horticulturae* 22:207-217
- Bruggink, G. T., H. E. Schouwink and E. A. J. M. Coolen. 1987. Effects of different day and night osmotic pressure of the nutrient solution on growth, water potentials and osmotic potentials of young tomato plants in soilless culture. *Soilless Culture* 3 (2):9-19
- Bruggink, G. T., H. E. Schouwink and Th. H. Gieling. 1988. Modeling of water potential and water uptake rate of tomato plants in the greenhouse: Preliminary results. *Acta Horticulture* 229:177-185
- Calvert, A. 1964. The effects of air temperature on growth of young tomato plants in natural light conditions. *Journal of Horticultural Science* 39:194-211
- Challa, H. May 81. Some remarks concerning the use of models in greenhouse climate. *Acta Horticulturae*. 107:117

Charbonneau, J., A. Gosselin and M. J. Trudel. 1988. Influence of electric conductivity and intermittent flow of the nutrient solution on growth and yield of greenhouse tomato in NFT. *Soilless Culture* 4 (1):19-30

Cooper, A. J. and D. Cooke. 1964. The effects of light intensity, day temperature and water supply on the fruit-ripening disorders and yield of two varieties of tomato. *Journal of Horticultural Science* 39:42-53

Cooper, A. J. 1972. The influence of container volume, solution concentration, pH and aeration on dry matter partition by tomato plants in water culture. *J. Hort. Sci.* 47:341-347.

Cooper, P. and F. J. Fuller. 1983. A transient model of the interaction between crop, environment and greenhouse structure for predicting crop yield and energy consumption *Agricultural Engineering Research*, p. 401

Cornillon, P. 1988. Influence of root temperature on tomato growth and nitrogen nutrition, *Acta Horticulturae*, 229:211.

Cornish, P.S. and V.Q. Nguyen. 1989. Use of high soil solution electrical conductivity to improve the quality of fresh market tomatoes from coastal New South Wales. *Aust. J. of Exp. Agr* 29:893-900

Costa, J., M. J. Dietz, F. Nuez, and G. Palomares. 1986. The influence of saline irrigation on tomato protected cultivation. *Acta Horticulturae* 191:107

Crop King, Inc. grower's school. 1993.

Dane, F., A. Gene Hunter and O. L. Chambliss. 1991. Fruit Set, pollen fertility, and combining ability of selected tomato genotypes under high temperature field conditions. *Journal of American Society of Horticultural Science* 116(5):906-910

Dhanvantari, B. N. and V. A. Dirks. 1987. Bacterial stem of greenhouse tomato: Etiology, Spatial distribution, and the effect of high humidity. *The American Phytopathological Society*. Vol 77(10):1457

Ehret, D. L. And L. C. Ho. 1986. The effects of salinity on dry matter partitioning and fruit growth in tomatoes grown in nutrient film culture. *Journal of Horticultural Science* 61(3) 361-367.

Fraser, J. M. 1992. Lecture notes on decision analysis. Industrial and Systems Engineering Department, The Ohio State University, Columbus, OH.

Fynn, R. P., 1988. A decision model for resource management using rule-based utility functions and parameter selection. Ph. D. Dissertation. The Ohio State University, Columbus, OH.

Fynn, R. P., W. L. Roller and H. M. Keener. 1989. A decision model for nutrition management in controlled environment agriculture. *Agricultural Systems* 31:35-53

Gislerod, H. R. , A. R. Selmer-Olsen and L. M. Mortensen. 1987. The effect of air humidity on nutrient uptake of some greenhouse plants. *Plant and soil* 102:193-196

Gohler, F. 1989. Control of water and nutrient supply in GH vegetable production by means of hydroponic systems. *Acta Horticulturae* 260:237

Gosselin, A., J. Charbonneau, L. -P. Vezina, and M. J. Trudel. 1988. Restrictions in Vegetative Growth of Tomato Plants Imposed by Altering the Nitrogen Concentration and the Electrical Conductivity of the Nutrient Solution. *Acta Horticulturae* 222:71

Gosselin, A. and M.J. Trudel. 1984. Interactions between root-zone temperature and light levels on growth, development and photosynthesis of *Lycopersicon Esculentum* Mill. Cultivar 'Vendor'. *Scientia Horticulture*, 23:313-321

Heuvelink, E. and L.F.M. Marcelis. Sep 89. Dry matter distribution in tomato and cucumber. *Acta Horticulturae* 260:149

Hildman, H. Sep 89. Testing a strategy of growth and yield control in GH cucumbers in a specialized vegetable-growing farm. *Acta Horticulturae* 260:123

Holder, R. and K. E. Cockshull. 1990. Effects of humidity on the growth and yield of glasshouse tomatoes. *Journal of Horticultural Science* 65(1):31-39

Hurd, R. G. and C. J. Graves. 1985. Some effects of air and root temperatures on the yield and quality of glasshouse tomatoes. *Journal of Horticultural Science* 60(3):359-371

Hurewitz, J. and H. Janes. 1983. Effect of Altering the root-zone temperature on Growth, Translocation, Carbon Exchange rate, and Leaf Starch Accumulation in the Tomato, *Plant. Physiol.* 73:46-50

Islam, A. K. M. S., D. G. Edwards, and C. J. Asher. 1980. pH Optima for Crop Growth: Results of a Flowing Solution Culture Experiment with six Species. *Plant and Soil* 54:339-357

Ismail, M. R. and S.W. Burrage. 1992. Effect of salinity, vapor pressure deficit and root temperature on growth and yield of NFT-Grown tomatoes. *Acta Horticulturae* 292:143

Jones, J. W. 1991. A dynamic tomato growth and yield model (TOMGRO). *Transactions of ASAE* 34 (2):663

Jones, P. 1990. Simulation for determining greenhouse temperature setpoints. *Transactions of ASAE*. 33(5): 1722-1728.

Kennedy, R. and G. F. Pegg. 1989. The Effect of root zone temperature on the control of *Phytophthora cryptogea* in rockwool-grown tomato plants, *Acta Horticulturae*. 238:165-171

Khayat, E., D. Ravad and M. Zieslin. 1985. Effects of various night temperature regimes on the vegetative growth and fruit production of tomato plants. *Scientia Horticulturae* 27:9-13

Kindelan, M. 1980. Dynamic modeling of GH environment. *Transactions of ASAE*. 23: 1232-1239

Koning, A. N. M de. 1988. Effect of different day/night temperature regimes on growth, development and yield of glasshouse tomatoes. *Journal of Horticultural Science* 63(3):465-471

Koning, A. N. M de. 1992. Effect of temperature on Development Rate and Length increase of Tomato, Cucumber and Sweet Pepper. *Acta Horticulturae*. 305:51

Krug, H. 1989. Growth models as an aid for planning vegetable production in GH. *Acta Horticulturae*. (260):391

Liebig, H. P. 1989. Growth and yield models as an aid for decision making in protected crop production control. *Acta Horticulturae* 260:99

Maletta, M and H.W. Janes. 1987. Interrelation of root and shoot temperatures on dry matter accumulation and root growth in tomato seedlings, *Journal of Horticultural Science* 62(1):49-54

McAvoy, Richard J. 1989. Validation of a computer model for a single-truss tomato cropping system. *Journal of American Society of Horticultural Science* 114(5):746-750

Munoz, R. Fernandez and J. Cuartero. 1991. Effect of temperature and irradiance on stigma exertion, ovule viability and embryo development in tomato. *Journal of Horticultural Science* 66(4):395-401

Nederhoff, E.M. 1989. Dynamic model for GH crop photosynthesis: Validation by measurements and application for CO<sub>2</sub> optimization. *Acta Horticulturae* 260:37

Papadopoulos, I. and V. V. Rendig. 1983. Interactive effects of salinity and nitrogen on growth and yield of tomato. *Plant and Soil* 73:47-57

Raiffa, H. 1968. *Decision Analysis: Introductory Lectures on Choices under Uncertainty*. Random House Publishing Company, New York.

Resh, H.R. 1989. *Hydroponic Food Production*. Woodbridge Press Publishing Company, Santa Barbara, California.

Rijsdijk, A.A. and G. Houter. 1993. Validation of a model for energy consumption, CO<sub>2</sub> consumption and crop production (ECP-model). *Acta Horticulturae* (328):125

Seginer, Ido. 1993. Crop models in greenhouse climate control. *Acta Horticulturae* (328):79

Siraj-Ali. 1985. Influence of nutrient solution pH on the availability and uptake of plant nutrients and growth of chrysanthemum morifolium 'Bright Golden Anne' in hydroponic culture. Dissertation. The Ohio State University, Columbus, OH.

Seyd, Werner and Carmen Feller. Sep 89. The vegetable production monitoring and control system (VPMCS) a combination of computerized technological planning, crop management and analysis. *Acta Horticulturae*. 260:195

Tindall, J. A. , H.A. Mills and D.E. Radcliffe. 1990. The effect of root zone temperature on nutrient uptake of tomato. *Journal of plant nutrition* 13(8):939-956

Von Neumann, J. and O.Morgenstern. 1947. *Theory of Games and Economic Behavior*. 2nd ed., Princeton, N. J.

Wallihan, E. F., R. G. Sharpless, and W. L. Printy. 1977. Effect of pH on Yield and Leaf Composition of Hydroponic Tomatoes. *HortScience*. 12(4):316-317

Wittwer, S.H. and S.Honma 1979. *Greenhouse Tomatoes, Lettuce and cucumbers*. East Lansing, Michigan State University Press.

Worley, R. E. 1972. Response of Tomato to pH of a Coastal Plain Soil. *Journal of American Society of Horticultural Science* 101(4):460-462

Yang, X., T. H. Short, R. D. Fox, and W. L. Bauerle. 1990. Dynamic modeling of the microclimate of a greenhouse cucumber row-crop. Part I: Theoretical Model. *Transactions of ASAE* 33(5):1701-1709 and 1701

**APPENDIX A**  
**EXAMPLE OF THE VALIDITY TEST GIVEN**  
**TO THE EXPERTS**



Expert's name:

Date:

Please follow the following instructions:

1. Mark next to each test result whether the corresponding value is acceptable (A) or unacceptable (U) for producing the best hydroponic tomato crop knowing the given growth stage and the weather conditions (The growth stages are defined in the next page).
2. Imagine you are now inside the greenhouse and you knew about those unacceptable test results, prioritize them in terms of the ones that need to be fixed first. Assume you have a reasonable control over each of the five test parameters.
3. The following is a complete example to demonstrate what need to be done.

Input set # Example

\* The current growth stage is the vegetative stage.

\* The weather condition is Night.

Test	Value	A or U	Priority
1. ECF (micromhos/cm)	9100	A (U)	(1) 2 3 4 5
2. pHF	6.5	(A) U	1 2 3 4 5
3. RTEMP (deg C) (deg F)	15.6 60.2	A (U)	1 2 3 (4) 5
4. ATEMP (deg C) (deg F)	16.8 62.2	A (U)	1 (2) 3 4 5
5. RH (%)	46	A (U)	1 2 (3) 4 5

where:

ECF is the electrical conductivity of the feeding solution.  
 pHF is the pH of the feeding solution.  
 RTEMP is the root temperature.  
 ATEMP is the air temperature inside the greenhouse.  
 RH is the relative humidity inside the greenhouse.