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PEPPER AND TOMATO SEED PERFORMANCE IN RESPONSE TO IMBIBITION AND DEHYDRATION

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ABSTRACT

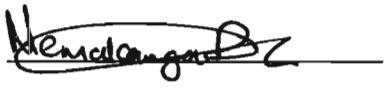
The International Seed Testing Association and the Association of Official Seed analysts define seed vigour as the ability of a seed lot to perform during the germination process and crop stand establishment under a wide range of environmental conditions. There are many ways to determine seed vigour, but few satisfy the requirements of being simple, inexpensive and reproducible, among others, to permit the seed industry to adopt seed vigour as an indicator of seed quality when they sell seeds. Hence, the standard germination test, which is performed under uniform and favourable conditions, is generally used to indicate seed quality when seeds are marketed. The objective of this study was to determine the performance of tomato and pepper seeds in response to pre-germination hydration and dehydration relative humidities (12%, 49% and 75% RH). Before hydration, seeds were hydrated at three temperatures (10°C, 20°C and 30°C). Hydration was performed by imbibing pre-weighed pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') seeds for 2 h in 10 ml of distilled H_2O per 100 seeds at 10°C, 20°C and 30°C. Dehydration was performed by change in seed mass determined during a 72-hour dehydration at 12%, 49% and 75% RH. Seed performance in response to imbibition and dehydration was determined by leakage of electrolytes from seeds during imbibition, laboratory germination capacity and seedling emergence under simulated shadehouse nursery conditions. A pot experiment was conducted to determine the effects of seed treatments on yield. Seed mass increased by about 50% during the 2-hour of hydration. Dehydration was hastened by decreasing the RH, and 12% RH significantly ($P < 0.05$) reduced the post-imbibition seed moisture content compared with 49% and 75% RH. The latter two relative humidities reduced the seed moisture content to about 10% and 15%, respectively, for all cultivars, irrespective of imbibition temperature. Low imbibition temperature (10°C) significantly ($P < 0.01$) increased electrolyte leakage, compared with high imbibition temperatures (20°C and 30°C), which were not significantly different from each other. At all hydration temperatures, low RH (12%) caused a significant ($P < 0.01$) decrease in seed germination whereas 49% RH and 75% RH apparently had a priming effect on seeds. There was no significant

difference between imbibition temperatures, with respect to seed germination, but 10°C caused a significant decrease in germination index, a measure of seed vigour. Seedling emergence was significantly ($P < 0.01$) reduced by both low imbibition temperature (10°C) and low dehydration relative humidity (12% RH). The negative effects of low imbibition temperature and rapid dehydration at 12% RH were also observed as stunted seedling growth.

Principal component analysis and linear regression were used to determine a statistical model to predict seedling emergence from germination percentage. The model predicted emergence consistently, but it overestimated it by about 2% to 3%. It is concluded that low imbibition temperature and rapid dehydration can be used to simulate stress to determine seed performance in pepper and tomato.

DECLARATION

I, Rendani Nemakanga, certify that the research work reported in this dissertation is my own original investigation, unless acknowledged, and has not been submitted to any other institution. The research was carried out at the University of KwaZulu-Natal, Pietermaritzburg, South Africa.



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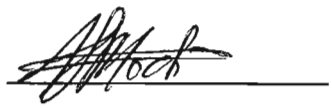
Approved by 

Dr Albert T. Modi

Supervisor

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CHAPTER 1 LITERATURE REVIEW

1.1 Introduction

Evaluation of seed planting quality for agricultural, horticultural and forestry purposes has been practiced since 1869 (Copeland and McDonald, 1995), yet seed scientists and propagation technologists continue to seek reliable methods for testing seed quality. Seed quality is a term used to reflect the overall value of a seed lot for its intended use (Bradford, 2004). Producers generally put their trust in seed companies to produce seeds of high quality. The quality of seeds plays an important role in determining seedling emergence, which in turn influences yield (Mazibuko and Modi, 2005). Therefore, poor seed quality is undesirable to producers since it contributes to reduction of crop yield resulting from poor germination and poor seedling uniformity. The quality of a seedlot determines whether seedlings produced will be able to withstand unfavorable environmental conditions in the field (Copeland and McDonald, 1995; Makkawi *et al.*, 1999).

Seed quality can be determined with various procedures depending on the objectives of the researcher and (or) availability of equipment. However, a useful seed quality measurement should be one that can easily and quickly address the needs of the seed companies, seedling producers and farmers. Seed quality is measured by two main components: Physical purity and physiological quality (Korkmaz *et al.*, 2004; Sako *et al.*, 2001; Pekÿen *et al.*, 2004, Bradford, 2004). Physiological seed quality is normally tested by seed vigour tests (Copeland and McDonald, 1995).

1.2 Physical seed quality

Seed purity denotes the physical composition of a seedlot. Therefore a seed purity test is concerned with the physical determination of contaminants in a seedlot, such as seeds of other crops, weed seeds and inert matter. The criteria

for distinction of pure seed from contaminants are explicitly defined in the Rules for Testing Seeds (AOSA, 1991).

Of interest in the present study is the philosophy of seed purity testing, which is to avoid judging whether seeds are capable of germinating when performing the test. This approach suggests that physically impaired seeds (e.g. shrivelled, frosted, immature or otherwise damaged) qualify to be included as pure seeds. Consequently, the evaluation of seed quality does not give an indication of seed performance for crop production purposes until a germination test has been performed. Hence upgrading, elimination of poor quality seeds, is necessary before a final decision is made about seed purity (McDonald and Copeland 1997). The concept of upgrading is reflected in terms of pure live seed percentage, which is calculated by multiplying the percent of purity and the percent of germination, expressed as fractions (McDonald *et al.*, 2000). Clearly, the pure live seed content provides a more realistic determination of seed quality than the purity tests alone.

1.3 Physiological seed quality

The ability of a seed to perform metabolic processes during germination and to produce a seedling under both controlled and field conditions is largely influenced by physiological quality (Korkmaz *et al.*, 2004). Seed viability, germination and vigour are the three attributes of physiological seed quality used by both seed technologists and biologists.

1.3.1 Seed viability

According to Copeland and McDonald (1997) seed viability is the degree to which a seed is alive, metabolically active and possesses enzymes capable of catalyzing metabolic reactions needed for germination and seedling growth. Thus, a viable seed may have live and dead tissues. The degree of viability therefore is likely to be correlated with the amount of seed tissue that is able to support enzyme activity and metabolic activity. It is conceivable that the highest

seed quality, as determined by seed viability, will be displayed by fresh seeds. Seeds that have been subjected to storage conditions over a long period of time may have less viability and eventually no viability (Gardner *et al.*, 1985).

From the definition of seed viability above, it is clear that seed germination can be used as a measure of seed viability. Measurement of metabolic activity can take many different approaches. Hence, there are many approaches to determine seed viability. Some of the approaches, and the basic principles involved in them are listed below:

Tetrazolium test: It distinguishes between viable and dead tissues of the embryo on the basis of their relative respiration rate in a hydrated state. The activity of dehydrogenase enzymes is used as an index of respiration rate and seed viability (AOSA, 1983).

X-Ray test: It is most often used within species with woody seed coats and a high frequency of empty seeds. Detection of insect damage, empty seeds, polyembryony, weathering and mechanical injury are determined by exposing seeds to x-rays. Seeds can be planted following the *x*-ray to determine germination (ISTA, 1999).

Hydrogen peroxide test: It has been suggested to enhance seed performance by accelerating the early respiration phase of seed germination. A small portion of the seed coat is cut at the root end and seeds are allowed to soak in hydrogen peroxide. This results in rapid radicle protrusion (Copeland and McDonald, 1997).

Fast Green test: It reveals physical fractures in the seed coat of light coloured seeds. Seeds are soaked in 0.1% solution of Fast Green stain for 15 to 30 minutes, washed and deformations marked by green colour are visually determined (Copeland and McDonald, 1995).

Indole acetate test: The principle for this test is similar to that of the Fast Green test in that it determines seed coat integrity (French *et al.*, 1962).

Sodium hypochlorite test: This method also reveals seed coat damage. After soaking in a solution of sodium hypochlorite, seeds with cracked seed coats

absorb the solution quickly and swell to three times their original size and can be separated easily from seeds with intact seed coats (Copeland and McDonald, 1995).

Conductivity test: The test is based on the premise that as seeds deteriorate, all membranes are damaged and soluble substances leak out of them, thus causing an increase in electrical conductivity in the water surrounding the seed (Copeland and McDonald, 1995).

Free fatty acid test: Degradation of fatty acids under high moisture and high temperature conditions can be used as a broad indication of deteriorating seed quality (Copeland and McDonald, 1995).

1.3.2 Germination test

To a physiologist, seed germination refers to radicle protrusion through a seed coat. This definition of seed germination suggests that seed germination is a physiological attribute that is used to test seed viability (McDonald and Copeland, 1997). However, seed viability may not be correlated with seed quality, because viability basically indicates that a seed is alive and metabolically active (Copeland and McDonald, 1995). It has been reported that a seed germination test is an imperfect tool to measure seed performance in the field, because it takes place under sterile and controlled environmental conditions, which do not exist under field conditions (Makkawi *et al.*, 1999; McDonald, 1999). This implies that seed germination may not be an accurate predictor of field performance (Pekÿen *et al.*, 2004).

To a seed technologist, seed germination is emergence and development from the embryo is one of those essential structures that determine whether the seeds of the particular species are able to produce a normal seedling or not under favourable conditions (AOSA, 1991). This definition suggests that seeds will germinate for a period of time that goes beyond radicle protrusion to include a physical state when seedlings have attained morphological characteristics

indicative of a normal seedling for the species at hand. Hence, seedling evaluation is important to determine seed quality during germination tests.

Germination results are used in determining seedlot suitability for sowing and comparing different seedlots' values to provide a basis for trade in seeds (Roberts, 1972). Germination capacity declines as seed ages during seed storage but complete death is preceded by the production of abnormal seedlings. At the end of a germination test, seeds considered non-viable must be separated to identify dormant seeds and dead seeds. Embryo condition plays a role in differentiating between dead seeds (whose embryo is soft and watery) and dormant seeds (whose embryo is firm to the touch). Hard seeds are recognized easily because they have not imbibed (Roberts, 1972). Sometimes seeds may be unable to germinate because they are non-viable or dormant. Therefore, in order to conclude about seed quality, it is important to establish the seed dormancy status before viability (including germination) tests (McDonald and Copeland, 1997).

Seedlings are evaluated in accordance with criteria pertaining to a species. Generally, development of critical organs (root tip, shoot tip, cotyledons, intact hypocotyl, etc.) indicates normal seedlings. A normal seedling is a seedling with complete shoot and root organs, whereas an abnormal seedling is one that is defective in some way and doesn't meet the criteria of a normal seedling. Common abnormal seedlings include stunted roots, failure of meristems to grow and curling hypocotyls.

Performance of seeds during the three phases of germination (Bewley and Black, 2000) can be used to determine seed quality. During phase I, imbibition occurrence (success or failure of a seed to absorb water) determines seedhardedness (Bewley and Black, 1994). Hence, a seed lot characterized by seedhardedness may be viewed as a poor seedlot. Hardseededness is a genetic

trait, but it can also be influenced by environmental conditions during seed development and maturation (Copeland and McDonald, 1995).

Rapid imbibition, on the other hand, has been associated with imbibition injury (Custidio and Marcos-Filho, 1997), indicated by leakage of substances essential for the growth of the embryo during germination (Modi and McDonald, 1999). Thus, leakage of substances early during seed hydration could be used as a measure of seed quality, particularly if the leakage is correlated with seed germination (Modi, 2005).

1.3.3 Seed vigour

Vigour is a seed property that determines their performance under a wide range of environmental conditions during germination and seedling growth (AOSA, 1983, ISTA, 1999). TeKrony and Spears (2000) argued that the definition of seed vigour as stated by Association of Official Seed Analysts (AOSA) and International Seed Testing Association (ISTA) merely describes the practical consequences of seed vigour. Vigour is an index of seed performance that can be described by several seed characteristics associated with various aspects of seed and seedling performance. The exact contributions of, and interaction between, these seed properties are not fully understood.

1.3.3.1 Pattern of seed vigour attainment and loss

Studies of seed development and maturation have shown that seeds are viable soon after fertilization, but do not reach maximum germination potential until late in maturation (Bewley and Black, 1994; Kermode, 1990; Long *et al.*, 1981). Maximum seed vigour occurs even later than maximum seed germination, because vigour closely associated with accumulation of nutrient reserves in the seeds (Bewley and Black, 1994). Maximum dry matter accumulation in seeds is attained at physiological maturity, when seeds no longer require support from the mother plant, through the funiculus (Copeland and McDonald, 1995).

Seed desiccation on the mother plant is accompanied by loss of seed quality. According to TeKrony and Spears (2000), the loss in seed quality continues during seed storage, and the most sensitive seed quality attribute to seed quality loss is seed vigour (Figure 1.1). Seed germination is less sensitive to seed deterioration than seed vigour, and seed viability is less sensitive than seed germination (Figure 1.1). Seed deterioration after maturation and during storage is influenced by genetics and environmental conditions associated with crop management and handling (Copeland and McDonald, 1995).

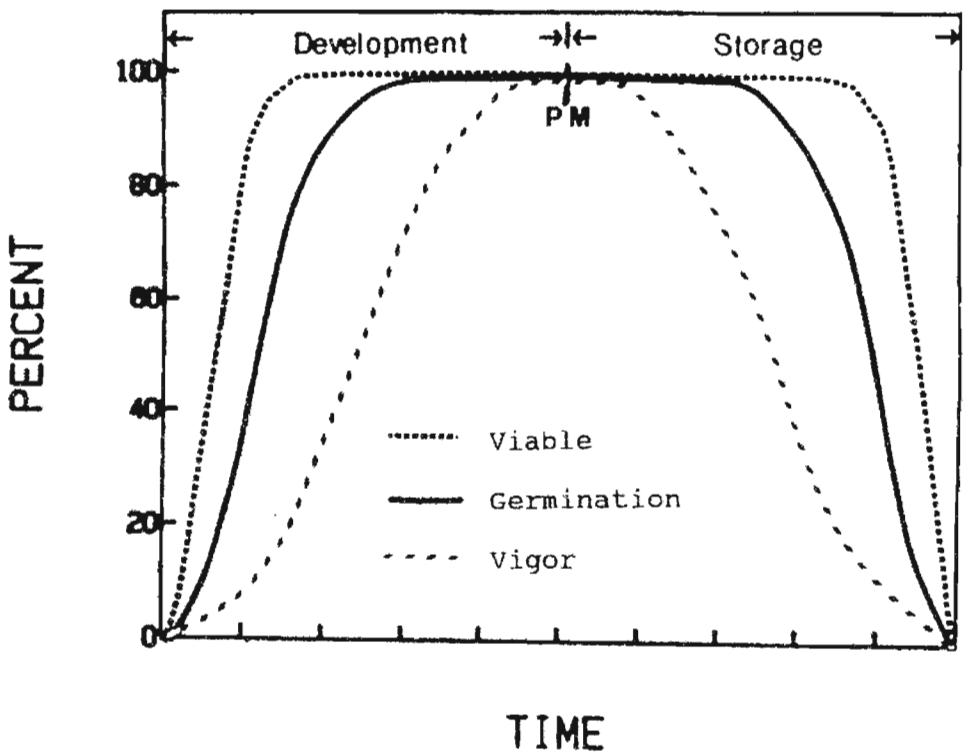

Figure 1.1. Pattern of attainment and loss in seed quality (TeKrony and Spears, 2000). Note: PM = Physiological Maturity.

1.3.3.2 Characterization of seed vigour loss

Seed deterioration has come to be recognized as the major cause of seed vigour loss (Hampton and TeKrony, 1995). Deterioration in seeds is generally progressive and sequential (Copeland and McDonald, 1995), but it is difficult to separate primary causes from secondary effects. Physiological and physical

damage to cell membranes is likely to be the fundamental cause of seed deterioration (Modi, 2005). Enzymatic, respirational and hormonal changes, impaired protein and RNA synthesis, and accumulation of toxic metabolites have also been implicated (Gurusinghe *et al.* 1999; Koehler *et al.* 1997). Among the key performance indicators of progressive loss in seed vigour are reductions in the rate and uniformity of germination, reduced tolerance to environmental stresses and inferior seedling emergence and growth (Figure 1.2).

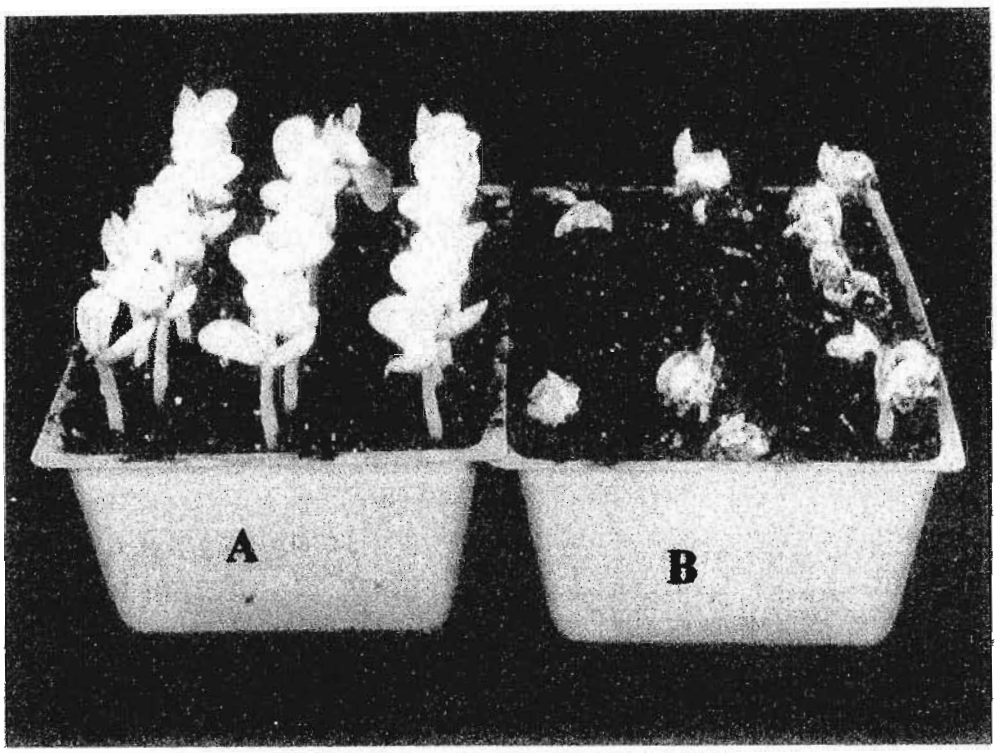

Figure 1.2. Effect of high seed vigor (A) on seedling emergence and growth compared to seedlings with low vigor (B) (Copeland and McDonald, 1995).

It is important to note that loss of seed vigour precedes the loss of ability to germinate (Figure 1.1). Therefore, the results of seed germination conducted after a period of seed storage are not likely to indicate accurately the degree of seed deterioration that has taken place. For example, two seed lots may have similar germination potential, but differ significantly in seed vigour (Table 1.1).

Table 1.1. Germination and emergence of two seedlots to illustrate differences in seed vigour (emergence) under a wide range of environments (fields) (TeKrony and Spears, 2000).

Seedlot	Germination (%)	Seedling emergence (%)		
		Field 1 (Near ideal conditions)	Field 2 (Slightly unfavorable conditions)	Field 3 (Very stressful conditions)
A	90	88	80	70
B	90	87	60	40

Accepting that seedling emergence is an important component of seed vigour (Copeland and McDonald, 1995) data shown in Table 1.1 illustrate that 1) seedlots with high laboratory germination may be low in vigour as shown by the sharp deviation of seedling emergence of seedlot B in fields 2 and 3, 2) even high vigour seedlots (A) display lower emergence than germination under conditions that are not as sterile as the laboratory (compare seed germination and emergence for seed lot A) and 3) under near ideal conditions, differences between vigorous and non-vigorous seedlots are minimized as indicated in field 1).

Assessment of seed vigour is complex, because the factors influencing seed vigour span physical and physiological phenomena. The complexity associated with determination of seed vigour means that it is difficult to standardize seed vigour testing, unlike seed germination testing. Notwithstanding the difficulties associated with its determination, seed vigour can be tested using methods that are described in detail in the handbooks of vigor test developed by the AOSA

and ISTA. The methods of seed vigour tests are grouped into three general categories: Stress tests (cold test, accelerated aging); Biochemical tests (conductivity test, tetrazolium test) and Seedling Growth and Evaluation tests (first count of germination, seedling growth rate and seedling weight) (Bradford, 2004; Egli and TeKrony, 1995; McDonald, 1999).

1.4 Role of seed quality models in seed science

Many mathematical approaches are used to model the germination behaviour of seed populations and have the potential to be adapted for standard quality testing purposes (Toselli and Casenave, 2005). These models are useful because they provide knowledge about the seed behaviour of different vegetable crops that can be applied to management decisions. For example, seed germination rate models have been developed and they consider seed water potential (Ψ) and temperature (T) during germination and priming (Gummerson, 1986). It is known that during germination, water potential (Ψ) is reduced; therefore the hydrotime model was introduced to predict germination time related to seed water potential (Ψ) (Gummerson, 1986). It was observed from the hydrotime model that as seed water potential (Ψ) decreases, radicle emergence increases. The hydrothermal priming time model (Tarquis and Bradford, 1992) was developed from the hydrotime model and is used to quantitatively describe the seed germination response following discrete water potential. This model provides a predictive approach to identify the optimal priming treatment for a seedlot without extensive empirical tests. The parameters of the hydrothermal priming time model can be simply determined by germination rates at as few as two water potentials and two temperatures in order to predict priming duration required at a particular water potential (Ψ) and temperature (T).

The median germination rate is predicted by both, hydropriming and hydrothermal priming time models, but it should be noted that individual seeds vary in response to water potential (Ψ) and temperature (T). Mathematical

models based on characterizing the variation occurring in germination times among individual seeds in a population describe and quantify environmental and after-ripening effects on seed germination. Particularly the hydrothermal time model describes and quantifies temperature and water potential effects on seed germination. This model states that the germination time of a given seed fraction is inversely proportional to the amount by which a given germination factor (e.g. temperature or water potential) exceeds a threshold level for that factor. The hydrothermal time model provides an important method for understanding how environmental factors interact to result in the germination phenotype (i.e. germination pattern over time) of a seed population. Additionally other factors that influence seed dormancy and germination act by causing the water potential thresholds of the seed population to shift to higher or lower values. This relatively simple model can describe and quantify the germination behaviour of seeds across a wide range of environmental conditions and dormancy states, and can be used as an input to more general models of seed germination and seedling emergence in the field.

Toselli and Casenave (2005) indicated that the hydrotime model is useful in explaining germination as a function of variable water potentials by automatically generating germination time courses that simply respond to changes in water potential during imbibition. Therefore this simply shows that this model might be useful in interpreting and comparing the effect of enhancements such as priming on germination. Hydrothermal time models are useful in characterizing seedlots of different crops in seed science by measuring time taken by a particular seedlot to complete germination with temperature and water potential as important variables (McDonald, 1997). However, Finch-Savage *et al.* (2000) indicated that thermal time and hydrothermal time models have been derived and tested against data collected under constant conditions. These models are considered unrealistic since the thermal time model seems to underestimate germination time, whereas the hydrothermal time model overestimates germination time (Finch-Savage *et al.*, 2000). Threshold germination models are more useful in

predicting seed germination recorded under variable field conditions, i.e. seed vigour under field conditions (Finch-Savage *et al.*, 2000).

According to Ellis and Roberts (1980, 1981) seed quality models are used to predict the survival of seed lots after long term storage by using data taken during accelerated aging period and to produce a measure of seed lot quality which is a good indicator of seed vigour or field experiments. For example the Ellis - Roberts viability model helps in estimating potential seed longevity as a function of storage time at a given temperature and relative humidity (Bradford 2004; Ellis and Roberts 1980, 1981; Tang *et al.*, 2000).

1.5 Justification and study objectives

The initial step in attaining maximum yield is to obtain an acceptable plant population in the field, greenhouse or seedling tray. High quality seed is required to produce a uniform seedling stand rapidly. The word "quality" in describing seed performance has a connotation of excellence. Literature on seed quality, as indicated in the preceding sections, suggests that characteristics of excellence in seed quality vary from physical integrity to physiological and biochemical activities. Seed vigour testing has been accepted as the primary measure of seed quality, but it encompasses measures of seed metabolic activity (viability) and performance (germination, emergence and seedling growth).

Predominantly, the current measures of seed vigour that are used by the seed industry, and endorsed by AOSA and ISTA were designed for large-seeded species (e.g. maize and pulses). The usefulness of these methods for small-seeded species (e.g. most Brassicaceae and Solanaceae vegetables and flowers) is precarious, and likely do not produce satisfactory indications of seed vigour for small seeds.

Preliminary studies (Modi, 2005) showed that hydration-desiccation treatment of vegetable seeds could create a stress that may be used to indicate seed vigour.

In that study (Modi, 2005), one cultivar of one vegetable species (pepper) was tested for response to hydration, followed by dehydration at nearly room temperature conditions. A significant effect of low relative humidity during dehydration on seed performance was found.

Seeds are subjected to a variety of environmental conditions during the initial stage of germination (imbibition). Among the conditions that can be created under laboratory conditions is imbibition temperature. Cool temperatures conditions during imbibition could cause imbibition injury (Copeland and McDonald, 1995). The effect of imbibing seeds under high temperature conditions has not been shown, but it could be postulated that warm temperature conditions during imbibition would accelerate seed deterioration, if imbibition was followed by dehydration.

To test the hypothesis that vigour of fresh seeds can be affected by imbibition temperature and dehydration relative humidity, this study was designed to examine three *Capsicum annuum,* pepper cultivars ('Santarini' and 'California Wonder'), Chili and three *Lycopersicon lypercorsicum,* tomato cultivars ('Heinz,' 'Marondera' and 'Roma') under laboratory and greenhouse environmental conditions.

The objectives of the study were to:

- Examine the effect of imbibing seeds in distilled water at three temperatures (10°C, 20°C and 30°C) on membrane integrity and germination under laboratory conditions,
- Examine seed performance with respect to uniformity and rate of seedling emergence and seedling growth under simulated nursery conditions,
- Determine performance of treatments on fruit production and
- Develop a model to relate seed germination to other seed performance parameters in the laboratory and in the greenhouse.

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CHAPTER 2

EFFECT OF IMBIMBITION TEMPERATURE AND DEHYDRATION RELATIVE HUMIDITY ON SEED PERFORMANCE

2.1 Introduction

Seed performance can be enhanced in various ways to ensure that high quality seed is made available for sowing. According to Taylor *et al.* (1998) seed enhancement is a post-harvest treatment improving germination and seedling growth or facilitating delivery of seeds and other materials required at the time of sowing. Seed enhancement techniques performed on different seedlots include seed priming, coating and conditioning (McDonald, 1998). Seed priming is the process of seed hydration associated with seed performance improvement followed by seed re-drying (McDonald, 1998; Mazibuko and Modi, 2005). Priming methods include four techniques that are extensively used commercially by seed companies and many researchers/scientists, namely hydropriming, drum priming, osmopriming and matripriming (McDonald, 1998). According to Modi (2005) and Bewley (1997), hydropriming is a process of soaking and misting seeds in water and re-drying them before germination (radicle protrusion) is commenced. Osmopriming is a process that involves an osmoticum for the seeds to absorb only a certain amount of water. Matripriming involves water uptake by the seed with involvement of the matrix. The hydropriming technique is considered the simplest, because of low to none use of chemicals (Alvarado and Bradford, 1988). The disadvantage of hydropriming is that imbibition injury occurs to seeds that swiftly absorb water during imbibition (Mazibuko and Modi, 2005). Many studies indicate that hydropriming can also be accomplished by either drum priming where-in seeds are rotated in a drum with a specified amount of water introduced as a fine mist (Modi, 2005) or by allowing seeds to imbibe water on moistened blotters or gels.

Hydropriming has been successfully used on a number of crops: Pepper (Halpin-Ingram and Sundstrom, 1992; Jones and Sanders, 1987), tomato (Ali *et al.*, 1990; Argerich and Bradford, 1989; Penaloza and Eira, 1993), onion (Ali *et al.*, 1990) and cucumber (Gray *et al.*, 1990). Hydropriming, drum priming and osmopriming have been reported to be successful in improving seed germination percentage (McDonald, 1999; Naglreiter *et al.*, 2005).

Although priming can improve seed germination, it is also known to be associated with leakage of minerals and other nutrient substances from the seeds, if the integrity of seed membranes is weak (McDonald, 1999). The seed membrane becomes more permeable as seeds age. Therefore many substances in seeds such as sugars, amino acids, organic acids and various elements leach out in the presence of water (Modi, 2005). Electrical conductivity is normally used to measure leakage concentrations from seeds (Modi, 2005). Leakage of seeds can be associated with the poor integrity of cell membranes as determined by deteriorative biochemicals that impair the ability to re-organize and repair damage. Thus, low vigour seeds are those seeds with high electrolyte leakage during imbibition (McDonald, 1999). Poor laboratory germination and poor seedling performance were shown to be correlated with high electrolyte leakage in seeds (Modi, 2005). Environmental conditions during growth and germination, genetics and plant age affect seed vigour (Pekÿen *et al.*, 2004).

Low temperatures are believed to cause imbibition injury to seed of some species such as maize and beans during the early stages of germination (Pollock and Toole, 1966). If seeds are too dry when placed in water they suffer low leakage of cellular contents and may fail to germinate properly (McDonald, 1999). Wolk *et al.* (1989) reported that there was imbibition injury in bean seeds imbibed at low temperature. In the present study it is postulated that dehydrating seeds shortly after imbibition at warm temperature conditions accelerates seed deterioration. To test this hypothesis seeds of tomato and pepper were examined

in the laboratory for their performance in response to imbibition at three temperature regimes and three relative humidities.

2.2 Materials and methods

2.2.1 Seed material

Seeds of *Capsicum annuum*, pepper cultivars ('Santarini' and 'California Wonder'), Chilli and *Lycopersicon lypercorsicum,* tomato cultivars, ('Heinz', 'Marondera' and 'Roma') were obtained from Pro-seed CC, Pietermaritzburg, KwaZulu-Natal, South Africa. Seeds were produced in 2004.

2.2.2 Seed imbibition and dehydration

This procedure was conducted according to Modi (2005), except for the imbibition temperatures. Three replications of 100 seeds were imbibed in 10 ml of distilled water for two hours at three respective temperatures (10°C, 20°C and 30°C). Following imbibition, seeds were dehydrated at three respective relative humidities namely 12% RH, 49% RH and 75% RH using saturated LiCl, KNO_2 and NaCl solutions, respectively. The values were confirmed using a HOBO H8 logger (Onset Computer Corporation). Control seeds were neither imbibed nor dehydrated, as a pre-treatment. Seeds were dehydrated for four days (72 hours) at 20°C. Seeds were weighed every day and data on changes in seed mass were recorded.

2.2.3 Seed germination

For each cultivar, four replications of 20 seeds each per imbibition and dehydration treatments were germinated (AOSA, 1993) and seeds with radicle protrusions were counted daily for fourteen days. The germination Index (GI) was determined using the following formula (Scott *et al.,* 1983):

$$GI = \frac{\sum_{i=1}^{n} T_i N_i}{TN}$$

Where GI = germination index, T_i = number of days after sowing starting with the final day, N_i = total number of seeds germinated on day *i*, where *i*= day 1, 2, 3.... 14 and N = total number of seeds germinated. The method calculates an index, which describes seed vigour on a scale of 0 to 1, with values close to 0 indicating low vigour and a value of 1 indicating maximum vigour.

2.2.4 Seedling dry mass

Immediately after germination period, seedlings from four replications of 20 seeds each per imbibition and dehydration treatments were weighed and the mass (g) was recorded before placing them in labelled small brown envelopes. Seedlings dry mass was determined after oven drying (70°C) for two days.

2.2.5 Conductivity test

From each of the three replications of 100 seeds that were imbibed in 10 ml of distilled water for two hours at three respective temperatures (10°C, 20°C and 30°C) the distilled water (without seeds) that was used for imbibition was used to perform electrical conductivity test (EC) with the use of electrical conductivity meter (µS/cm) (Modi, 2005).

2.2.6 Statistical Analyse

All data were analysed using general statistical analyse (GenStat Release 7.0 Rothamsted Experimental Station, UK) to generate the analysis of variance (ANOVA) (Appendices 2.1 and 2.2) wherein differences between means were obtained at 5% least significant difference (LSD).

2.3 Results and discussion

2.3.1 Seed imbibition and dehydration

For all species and cultivars, imbibition caused an increase of about 49% in seed mass. The general pattern of water absorption and dehydration at all

temperatures is depicted in Figure 2.1. There were no differences between cultivars and imbibition temperatures with respect to hydration and dehydration. It is clear from Figure 2.1 that there was a significant water loss from seeds as the dehydration relative humidity was decreased from 75% to 12%.

Keeping imbibed seeds at 12% RH caused a rapid decrease in seed moisture content, followed by 49% RH while 75% RH caused seeds to maintain almost 15% moisture content after 72h of dehydration. Harrington (1960) reported that pepper seeds stored over saturated salts equilibrate to 2.5% moisture content at 10% RH, 6% at 30% RH and 9.2% at 60% RH. Hence, the data shown in Figure 2.1 confirmed the previous findings on the desiccation effects of saturated salts on seeds. Although the data on Figure 2.1 showed the seed mass increase, it is known that the higher the seed mass, the lower the loss of moisture content in the seeds and vice versa. Therefore is was observed that seeds dehydrated at 12% RH had high seed moisture content loss compared to seeds dehydrated at 49% and 75%RH (Figure 2.1).

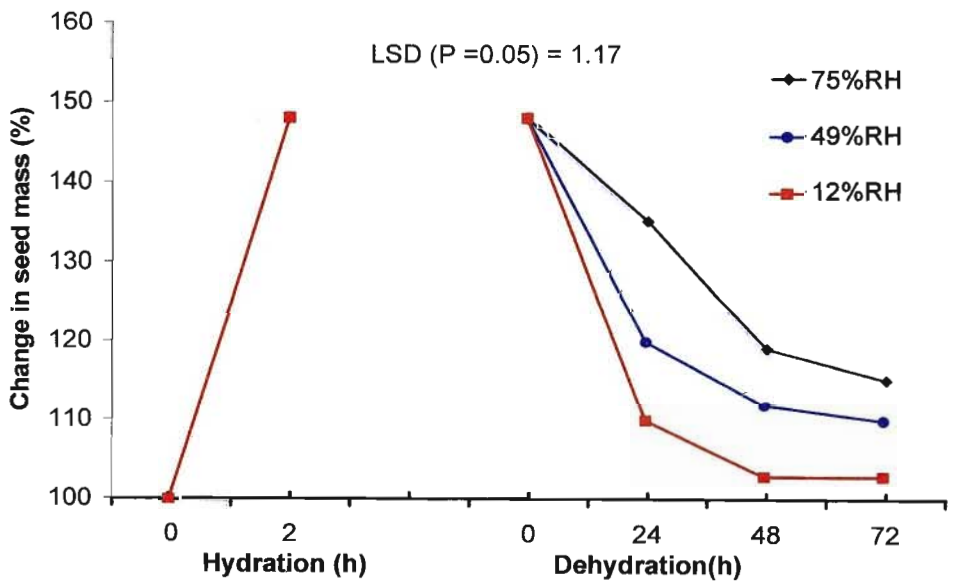

Figure 2.1. Changes in pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma') seed moisture content during 2 hours of hydration followed by 72 hours of dehydration over saturated salts at different relative humidities.

2.3.2 Leakage of substances from seeds during imbibition

There was a significant difference ($P < 0.001$) between cultivars with respect to solute leakage. Chilli and 'Santarini' pepper showed double the amount of conductivity compared with the one pepper 'California Wonder' and the tomatoes ('Heinz', 'Marondera' and 'Roma') (Figure 2.2).

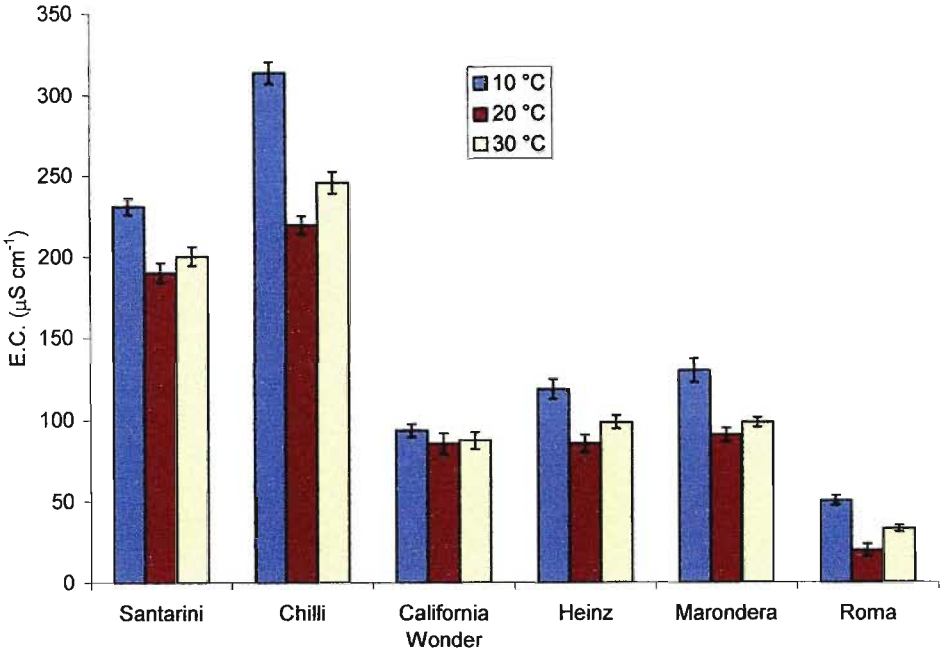

Figure 2.2. Leakage (EC) of soluble substances from pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma') during a 2-h imbibition period at three temperatures (10°C, 20°C and 30°C). Note: LSD ($P = 0.05$) = 24.43.

Although there were no significant differences between temperatures, there was a significant interaction between cultivars and temperature ($P < 0.01$), with respect to solute leakage from seeds. For pepper cultivars, Chilli and tomato cultivars seed leakage was increased by imbibition at 10°C. Although there was a tendency for 'California Wonder' to respond like 'Santarini', the tendency was not statistically significant (Appendix 2.2A).

Imbibing seeds at low temperatures is known to cause chilling injury, which is also referred to as imbibitional injury (Nijsse *et al.*, 2004). Therefore, the increased leakage of solutes at 10°C (Figure 2.2) is likely due to imbibitional injury. Imbibitional injury is an indication of reduced cell membrane integrity. It has been attributed to a membrane phase change from a gel phase to a liquid crystalline phase during water uptake (Crowe *et al.*, 1989; Hoekstra *et al.*, 1992). Defects at the boundary between gel phase domains and the liquid crystalline phase are responsible for the increased membrane permeability. In addition, when membranes are in the dry state, their rigidity is much higher than when they are in the hydrated state (Hoekstra and Golovina, 1999). Low temperatures promote gel phase formation and increase rigidity, thereby increasing the likelihood of imbibitional injury during fast absorption of water by a seed with low moisture content (Hoekstra and Golovina, 1999). The seeds used in the present study were at ~10% moisture content, which was a lot to cause rapid imbibition (Mazibuko and Modi, 2005).

Although it was not reflected in Figure 2.2 Chilli and 'Santarini' had relatively large seeds compared to the other cultivars, while Roma had the smallest seed size. It is likely that seed size had an influence on the response of seeds to imbibition. It is interesting to note that the larger seeds were generally less affected by low temperature imbibitional injury (Figure 2.2). Mazibuko and Modi (2005) reported a positive correlation between seed size and imbibition rate. Therefore, it is likely that in this study, the high leakage was associated with rapid imbibition by larger seeded cultivars compared to the smaller seeded ones.

2.3.3 Seed performance during germination

There were no significant differences between cultivars with respect to seed germination (Appendix 2.2B). Average germination for tomato and pepper cultivars ranged between seventy and ninety-seven percent (Figure 2.3). At all hydration temperatures, low RH (12%) caused a decrease in seed germination whereas 49% RH and 75% RH apparently had an enhancing effect on

germination that was similar to that of priming (Figure 2.3). There was no significant difference between imbibition temperatures, with respect to total seed germination (Figure 2.3).

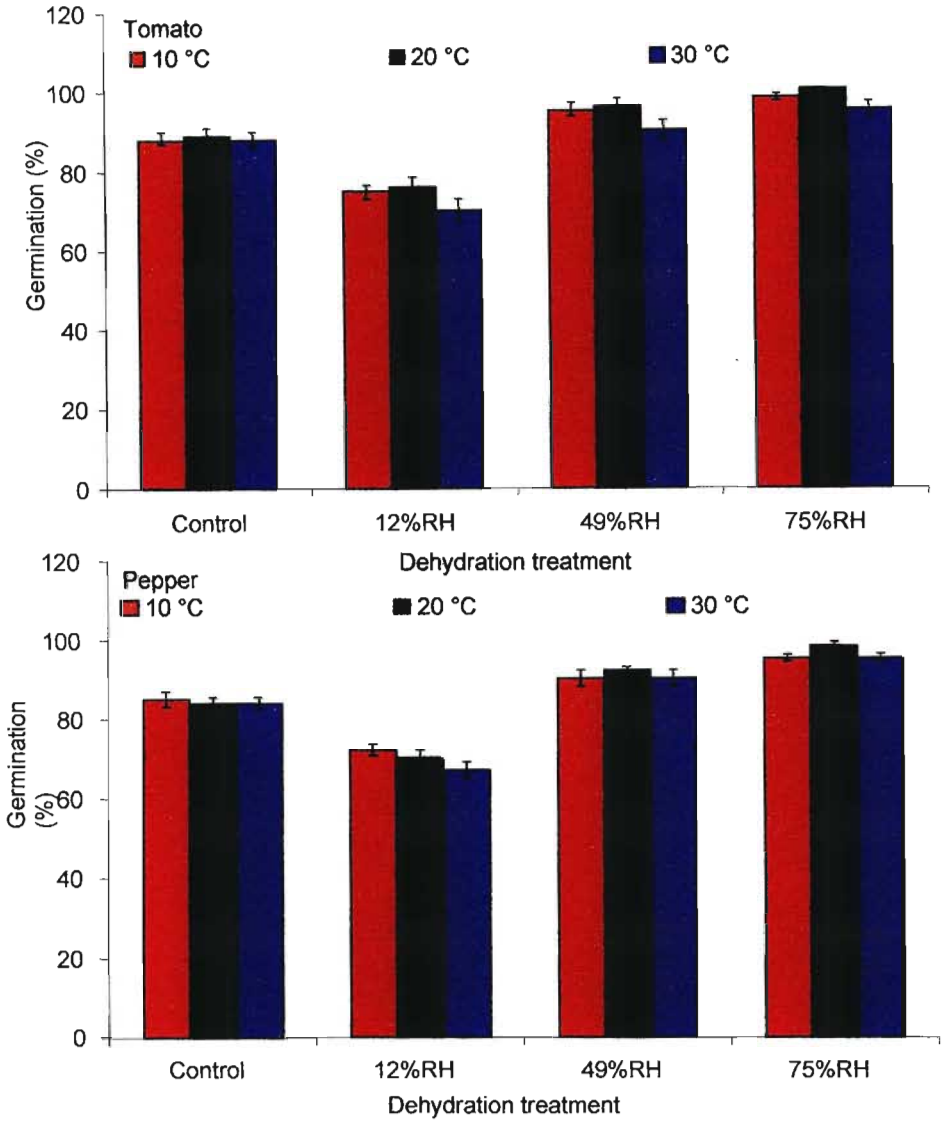

Figure 2.3. Effect of hydration temperature and dehydration RH on pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') seed germination. Control seeds were not hydrated.

Low RH (12%) reduced seed quality, as determined by seed germination (Figure 2.3). Low relative humidity dehydration could be associated with fast-drying, whereas dehydration at high relative humidity (e.g. 75%) could be associated with slow-drying (Modi, 2005). Fast-drying has been shown to decrease seed

quality in tomato (Penaloza *et al.*, 1993). In this study, the 75% RH allowed a high moisture content to remain in the seeds before germination was started (Figure 2.1). Increasing seeds to a high moisture content has been shown to improve seed germination (McDonald, 2000).

Total germination alone is not a good indicator of seed performance (AOSA, 1993). The vigour of seeds during germination can be determined by the rate of germination and the quality of seedlings produced in the final germination count. The commonly used measure of germination rate is germination index (GI).

The present study showed that there was a significant difference ($P < 0.01$) between cultivars, with respect to GI (Figures 2.4 to 2.7). On average 'Santarini' showed the highest germination index compared with the other cultivars, when seeds were dehydrated at 12% RH (Figure 2.4). However, there was no clear pattern of cultivar differences when seeds were dehydrated at 49% and 75% RH. The general pattern of GI shown at 12% RH was in agreement with the pattern for seed leakage (Figure 2.2). Seeds that were subjected to 12% RH after imbibition period showed a lower GI compared to controls and other seed dehydration RH treatments (49% and 75% RH).

There were also significant ($P < 0.01$) differences between imbibition temperatures, with respect to GI (Figures 2.4 to 2.6). Except for Chilli 49% RH, 'Roma' 49% RH, Chilli 75% RH, 'Heinz' 75% RH, 'Marondera' 75% RH and 'Roma' 75% RH, the rest of dehydration RH showed that imbibing seeds at 10°C caused a significant ($P < 0.001$) (Appendix 2.2C) decrease in GI (Figures 2.4 to 2.6). Imbibing seeds at 20°C improved GI compared to 10°C. Imbibing seeds at 30°C had a negative effect, however, it was still an improvement compared to imbibing at 10°C (Figures 2.4 to 2.6). Seeds that were not subjected to imbibition (control) showed a significantly higher GI than seeds subjected to imbibition and dehydration at 12% RH, irrespective of imbibition temperature (Figure 2.4). However, at 49% and 75% dehydration RHs there was a significant improvement

in GI, so that Chilli and 'Roma' showed no significant differences from the control when seeds were imbibed at 20°C (Figures 2.5 and 2.6).

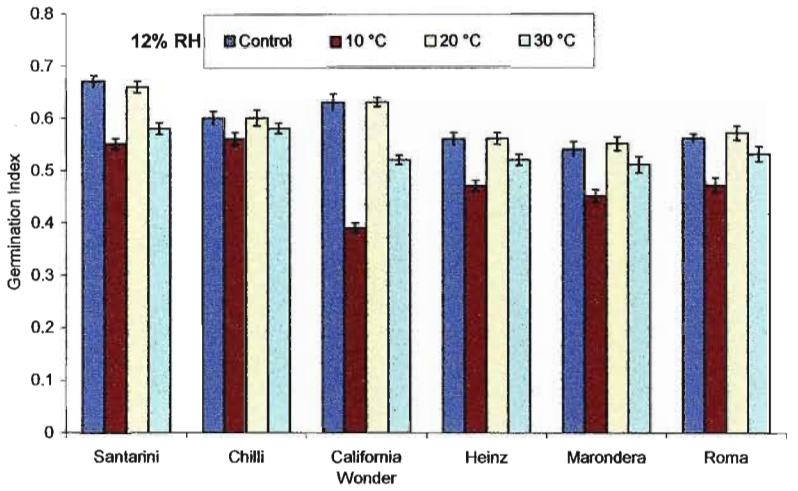

Figure 2.4. Germination index of pepper cultivars ('Santarini', and 'California Wonder'), Chilli and tomato cultivars ('Marondera', 'Roma' and 'Heinz') imbibed at different temperatures (inset) and dehydrated at 12% RH. Control seeds were not hydrated.

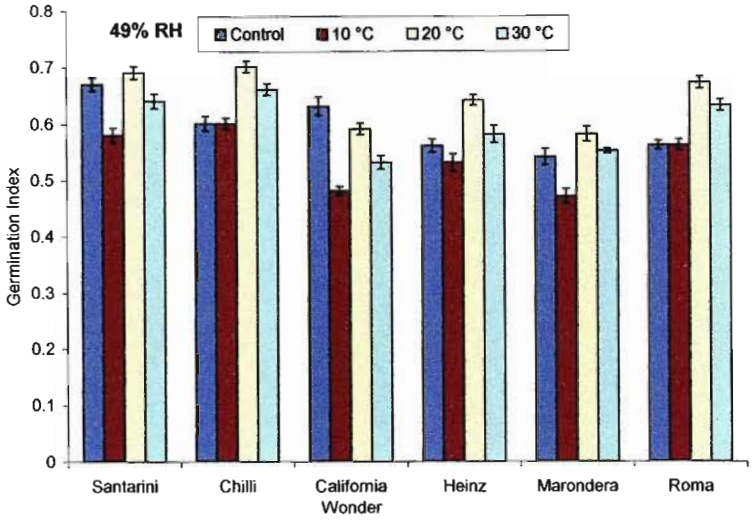

Figure 2.5. Germination index of pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma') imbibed at different temperatures (inset) and dehydrated at 49% RH. Control seeds were not hydrated.

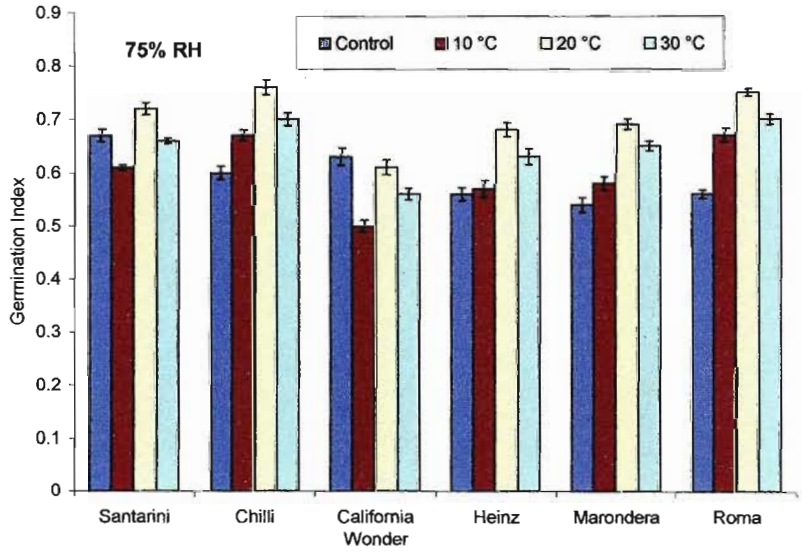

Figure 2.6. Germination index of pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz,' 'Marondera' and 'Roma') imbibed at different temperatures (inset) and dehydrated at 75% RH. Control seeds were not hydrated.

A comparison of dehydration relative humidities showed that 12% RH significantly ($P < 0.001$) reduced GI for all cultivars except 'California Wonder' compared with 49% RH and 75% RH (Figure 2.7). Imbibing seeds at 49% RH improved GI by 20% to 50%, and 75% dehydration RH caused an improvement of 50% to 100% in GI compared to 12% RH (Figure 2.6).

There was no significant difference between peppers and tomatoes, with respect to their response to imbibition and dehydration treatments in this study. However, data shown in Figures 2.4 to 2.7 suggest that 'California Wonder' and 'Santarini' were affected less by slow-drying (at high seed dehydration RH such as 75% RH) compared to Chilli, 'Heinz', 'Marondera' and 'Roma' (Figure 2.7).

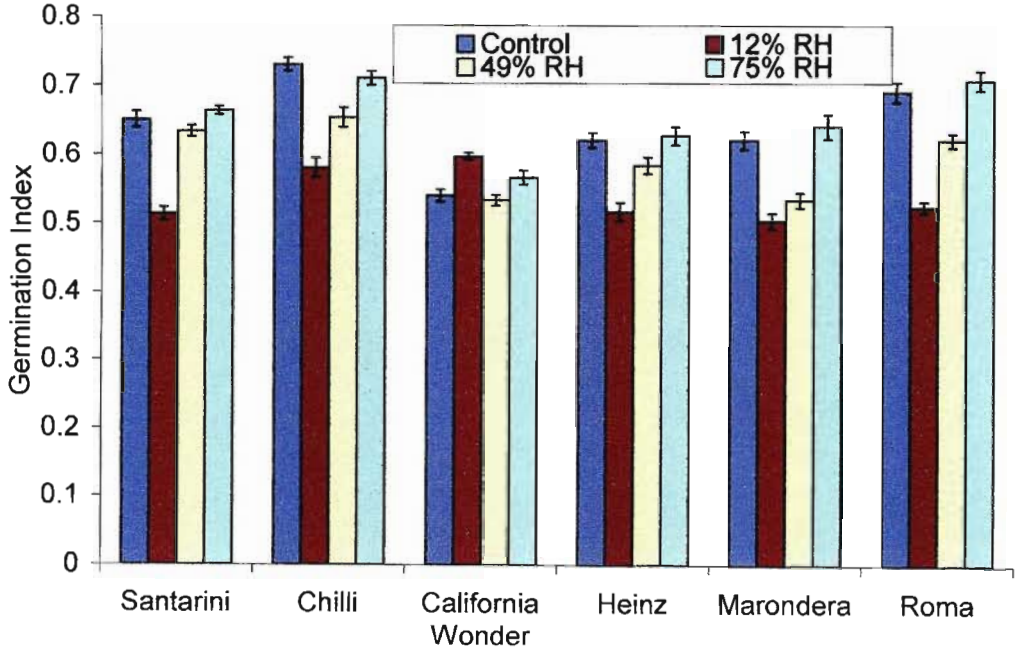

Figure 2.7. Effect of dehydration relative humidity on germination index of pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') seeds. Control seeds were not hydrated.

Since the germination index indicates the speed of seed germination, and hence, seed vigour, it can be deduced from Figures 2.4 to 2.6 that imbibing seeds at low temperatures (10°C) reduces seed vigour of pepper, Chilli and tomato seeds. It

can also be deduced that rapid dehydration of seeds at 12% RH exacerbates seed vigour loss. The loss of vigour can be minimized by imbibing seeds at 20°C and by slow dehydration at 75% RH (Figure 2.7).

Changes in seedling mass at the final germination count (day 14) in response to imbibition and dehydration treatments were similar to those of GI, except that Chilli and 'Santarini' displayed large seedling masses because of their relatively large seed sizes (Figures 2.8 to 2.10). The close agreement in patterns of GI and those of seedling mass confirms that the vigour of seeds is affected in the manner in which seeds germinate and in the size of seedlings produced from the seedlings. The small size of seedlings derived from seeds that were imbibed at low temperatures (10°C) and those that were rapidly dehydrated at 12% RH, may be due to damaged membrane integrity and subsequent loss of soluble substances (nutrients) required to support a germinating seedling (Figure 2.2) (Modi, 2005).

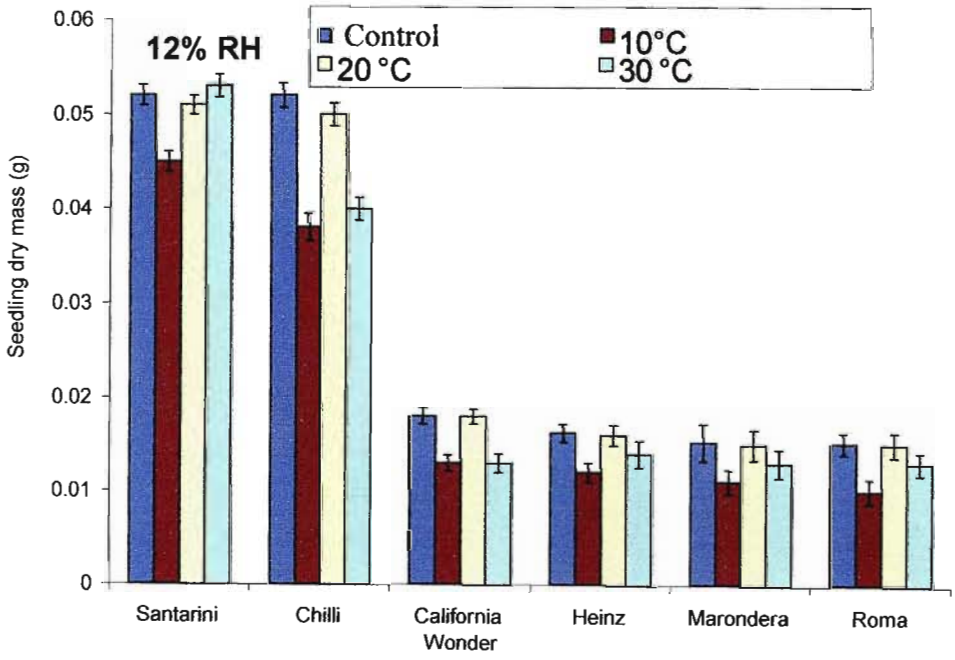

Figure 2.8. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') seedlings dry mass of seeds that were dehydrated at 12% RH. Seedling dry mass was determined at the final germination count in the laboratory. Control seeds were not hydrated.

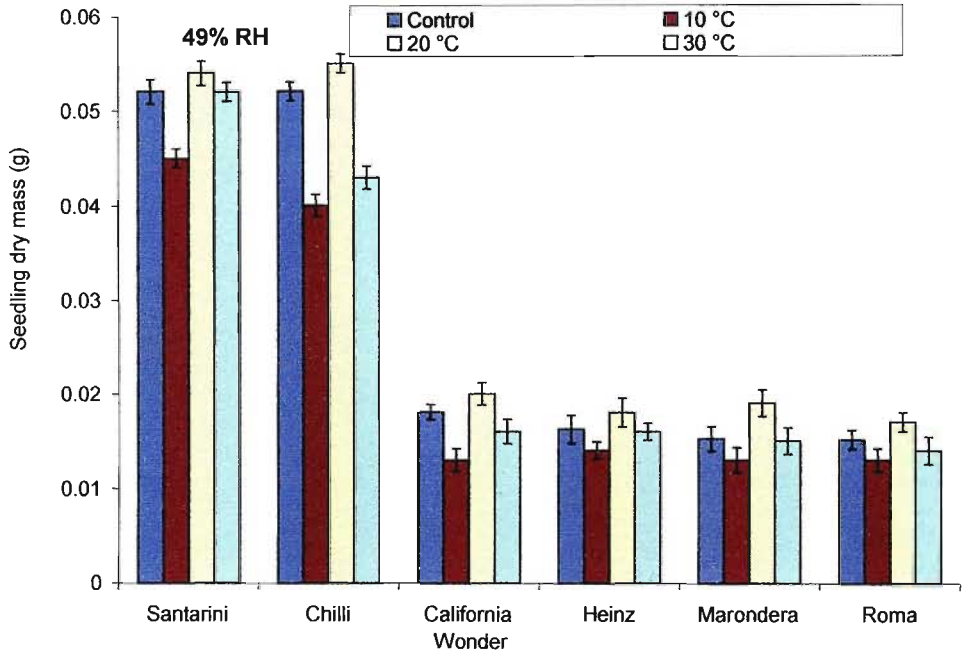

Figure 2.9. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') seedling dry mass of seeds dehydrated at 49% RH. Seedling dry mass was determined at the final germination count in the laboratory. Control seeds were not hydrated.

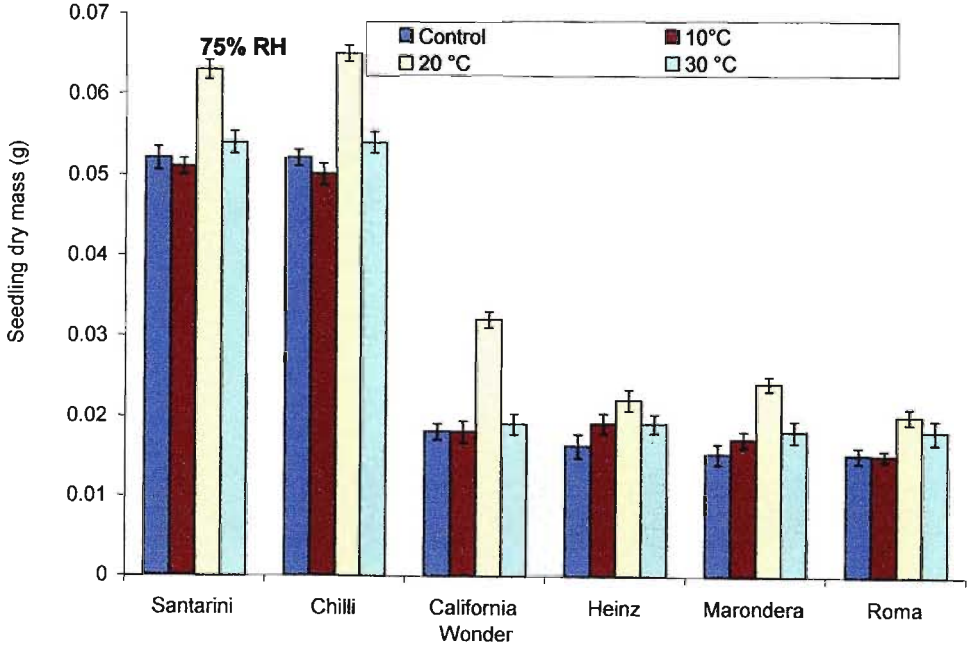

Figure 2.10. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') seedling dry mass of seeds dehydrated at 75% RH. Seedling dry mass was determined at the final germination count in the laboratory.

This study confirmed the previous findings that low temperatures cause imbibitional injury (Bradford, 2004; Hoekstra and Golovina, 1999). However, the study also showed that total germination alone is not a good indicator of seed quality (Figure 2.2). It is necessary to test for seed vigour (GI) and to subject seeds to some form of stress (dehydration) to detect seed quality.

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CHAPTER 3

EFFECTS OF SEED IMBIBITION TEMPERATURE AND DEHYDRATION RH ON PEPPER, CHILLI AND TOMATO SEEDLING EMERGENCE, SEEDLING DEVELOPMENT AND YIELD

3.1 Introduction

Seeds constitute 5 to 8% of the production cost in a nursery (Langenhoven, 2004). Therefore, seedling producers expect good performance from seeds, in the form of high and uniform emergence, uniform seedling growth and production of robust seedlings. Seed quality and environmental conditions have been shown to influence the rate and uniformity of emergence (Helsel *et al.,* 1986; De *et al.,* 2003). Slow emergence is associated with small seedlings (Ellis, 1989) and plants which are more susceptible to pathogens (Gubels, 1975; Osburn and Schroth, 1989). Extended emergence periods could expose seeds and seedlings to pathogen infection and harsh environments (Heydecker, 1978).

Studies on tomato (Haigh *et al.*, 1986) and pepper (Yaklich and Orzolek, 1977) have shown that priming improved seedling emergence. Priming is generally more successful for small-seeded vegetable crops compared with large-seeded green crops such as beans (McDonald, 2000). Use of priming to enhance seed performance may be followed by dehydration to allow ease of transporting and handling seeds (McDonald, 2000). In Chapter 2, it was shown that imbibition of pepper and tomato seeds can cause damage if it is done at low temperatures. It was also shown that dehydration at low relative humidity could have a negative effect on seed performance during germination. However, imbibition at ambient temperatures and slow dehydration at high relative humidities were shown to improve seed performance during germination. The objective of this study was to examine the effect of imbibition temperature and dehydration relative humidity on the performance of pepper and tomato seeds in seedling establishment.

3.2 Materials and methods

3.2.1 Seed material

Seeds of *Capsicum* species, pepper cultivars ('Santarini' and 'California Wonder'), Chilli and *Lycopersicon* species, tomato cultivars, ('Heinz', 'Marondera' and 'Roma') were obtained from Pro-seed CC, Pietermaritzburg, KwaZulu-Natal, South Africa. Seeds were produced in 2004.

3.2.2 Seedling emergence

Treatment of seeds before sowing was described in section 2.2.2. Seeds were planted in 128-celled (~38 ml $cell^{-1}$) Styrofoam seedling trays and emergence was determined daily after sowing. Seedling development was determined by the number of leaves formed from emergence for 14 days. Emergence and stand establishment were determined in a shadehouse. The environmental conditions during seedling growth are presented in Appendix 3.1.

The experiment was designed as split plot with saturated salt solutions as main plots and imbibition temperatures as sub plots. The experimental unit was formed by 10 cells per treatment and control (seeds not imbibed). The experimental cells were surrounded by border rows consisting of cells of the same treatment. Planting was performed by hand placing seeds about 2.5 cm into a seedbed filled with seedling mix (composted pine bark). Trays were automatically watered twice daily (10h00 AM and 15h00 PM; ~ 25 mm per day) from sowing and up to fourteen days from initial seedling emergence.

Seedling emergence data was collected and recorded from the second day after planting by counting the number of seedlings emerged daily per treatment (salt and relative temperature) for each cultivar. After completing the emergence test, the emergence index (EI) and emergence percentage (E %) were calculated as shown below from the total number of seedlings that had emerged.

$EI = \Sigma T_i N_i / S$

Where: EI = emergence index

T_i = day i (time) after sowing

N_i= number of seeds emerged on day i

S = total number of seeds planted per replication.

$E\% = (T/N)\ 100$

Where: T = total number of seeds germinated per replication after 14 days

N = total number of seeds planted per replication.

The emergence data were then analysed (ANOVA) as a nested design with the introduction of new treatments wherein 0 represented controls and 1 represented all treatments using GenStat Release 7.0 (Rothamsted Experimental Station, UK) (Appendix 3). Means were presented by graphs and tables (for high interaction) and the differences between means were determined by LSD (least significant difference) generated simultaneously as the ANOVA tables.

3.2.3 Seedling growth

Seedlings were transferred to a shade cloth (50% light) immediately after 14 days of completing emergence test. Seedlings were arranged and watered the same way as they were in the greenhouse. When seedlings were transferred to the shade-house no primary leaf had emerged. Hence, leaf number was counted initially in the shade-house. From each replication five seedlings were selected and plant height and leaf number were measured weekly for 10 weeks.

3.2.4 Seedling size determination

For each treatment (imbibition temperature and dehydration RH) and control, three seedlings were randomly selected to create three replicates. Seedling shoots were removed by cutting the seedlings at the base. Seedling shoot dry mass was determined after oven drying (70°C) for two days.

3.2.5 Transplanting

For each treatment and control, three seedlings were randomly selected to create three replicates. Each seedling was planted in a 30-cm pot (one replicate) containing composted pine bark. The pine bark was fertilised (1: 100 v/v) with organic fertiliser Neutrog® (Cato Ridge, South Africa) (N = 30 g kg^{-1}, P = 11 g kg^{-1}, P_2O^5 = 25 g kg^{-1}, K = 10 g kg^{-1}, K_2O = 12 g kg^{-1}, Ca = 25 g kg^{-1}, S = 6 g kg^{-1}, Mg = 8 g kg^{-1}, Zn = 443 mg kg^{-1}, Organic matter = 650 g kg^{-1}, moisture = 120 g $kg^{-1}$and the product density = 655 kg m^{-2}). Three pots per temperature per salt from controls and treatments were arranged in the shadehouse wherein each pot represented a replication. The pots were arranged in a split plot design. After transplanting seedlings, plants were watered daily (~25 mm per week) and plant height and leaf number were determined weekly until fruits were ready for harvesting.

3.3 Results and discussion

3.3.1 Seedling emergence

There was a significant difference between cultivars, imbibition temperatures and RHs ($P < 0.01$) with respect to seedling emergence (Figure 3.1). There was also a significant ($P < 0.01$) interaction between cultivar responses and treatment effects. Tomatoes cultivars ('Heinz', 'Marondera' and 'Roma') showed a higher emergence percentage than pepper cultivars ('Santarini' and 'California Wonder') and Chilli (Figure 3.1). Across all three RHs, imbibing seeds at low temperature (10°C) caused a significant reduction in seedling emergence compared with imbibition at 20°C and 30°C (Figure 3.1) (Appendix 3.2A). However, imbibition at 20°C and 30°C did not improve emergence of control seeds (untreated seeds) (Figure 3.1).

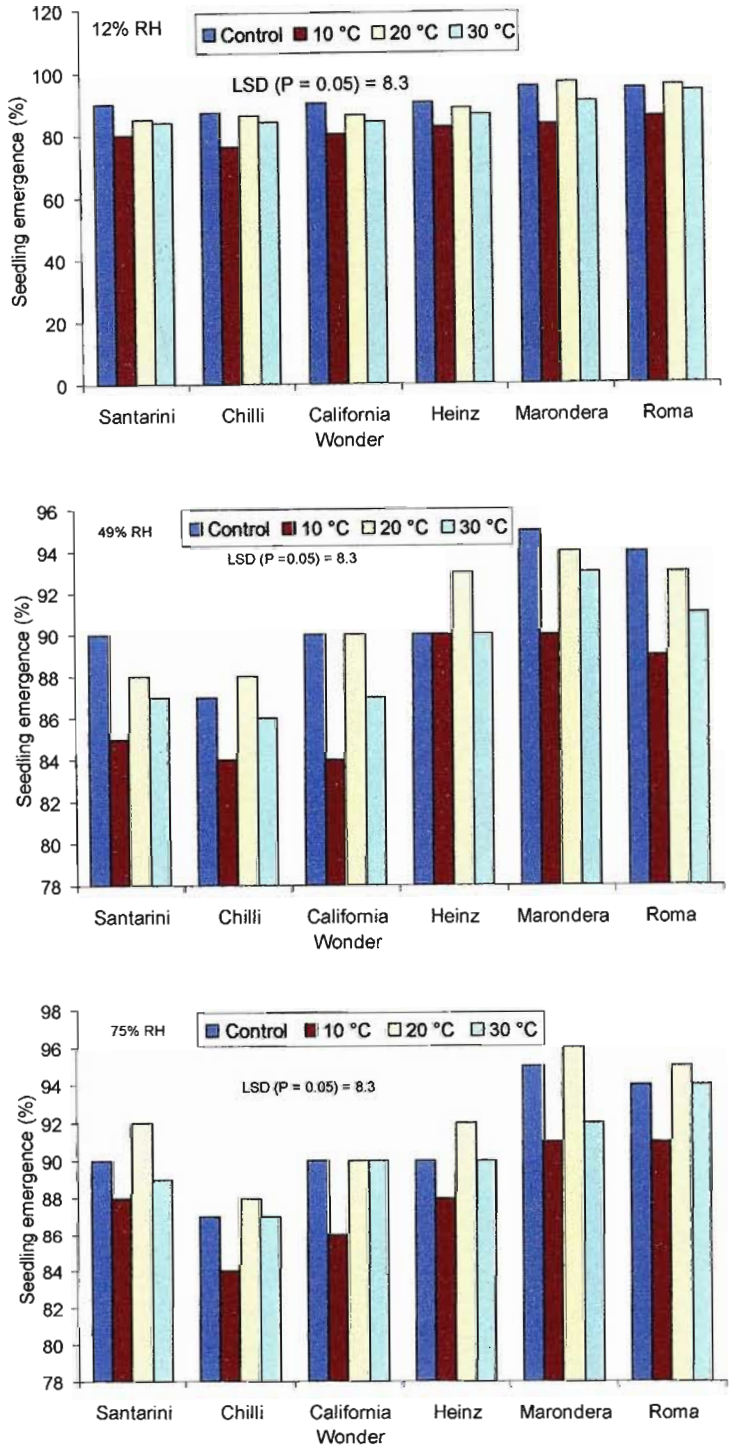

Figure 3.1. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') seedling emergence in response to imbibition temperatures (inset) and dehydration relative humidities (12, 49 and 75% RH). Control seeds were not hydrated.

Rapid seed dehydration (12% RH) significantly ($P < 0.05$) reduced seedling emergence, regardless of imbibition temperature or cultivar (Figures 3.1 and 3.2).

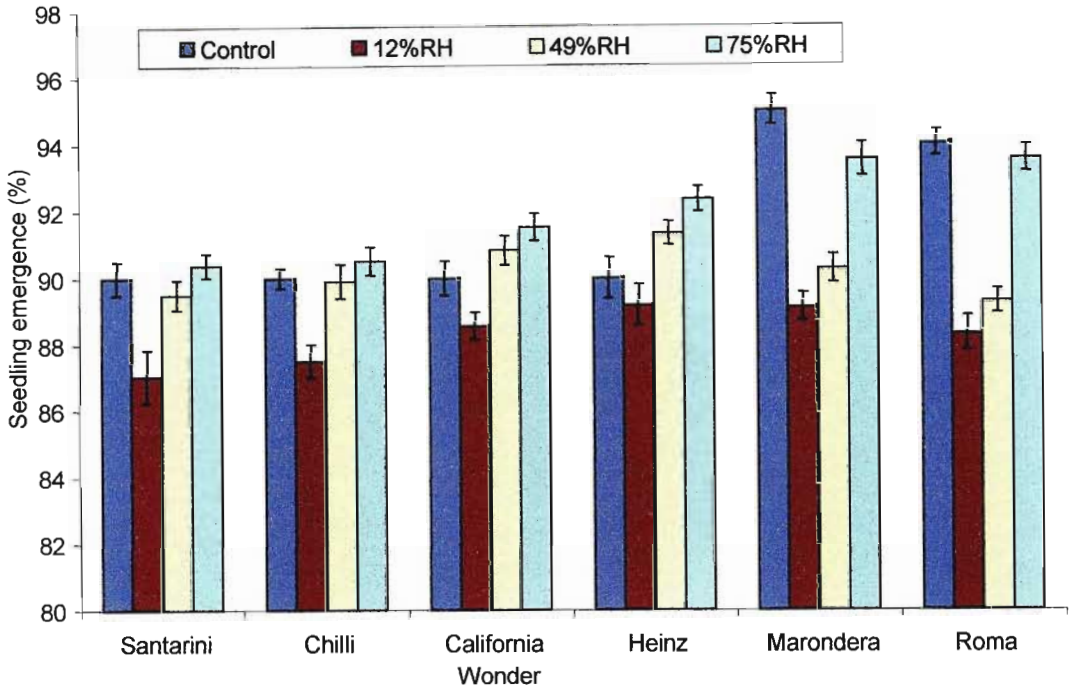

Figure 3.2. Seedling emergence percentages of pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma') as influenced by a dehydration RH. Note: LSD (P=0.05) =8.3. Control seeds were not hydrated.

There was a general improvement in untreated seedling emergence percentage in response to increased dehydration RH (49% and 75%), but only two cultivars, 'California Wonder' and 'Heinz', showed a significant ($P < 0.05$) improvement (Figure 3.2).

The results of this study concur with the findings about seed performance during germination (Chapter 2). Similar to the correlation of GI and G% (Chapter 2) there was a correlation between emergence percentage (Figure 3.2) and emergence index (EI) with respect to the effects of temperature and RH (Figures 3.3 and 3.4). However, seedling emergence was 2 to 5% lower than the

germination percentage. The decrease of emergence compared with germination has been shown in a previous study on pepper (Modi, 2005). The difference in germination and emergence percentage may be attributed to germination conditions being favourable and sterile, compared with the environmental conditions during emergence, which are subject to less control of the microclimate. Further, there are possible negative effects of media, chemical, physical and biological conditions (Van Schoor *et al.*, 1990).

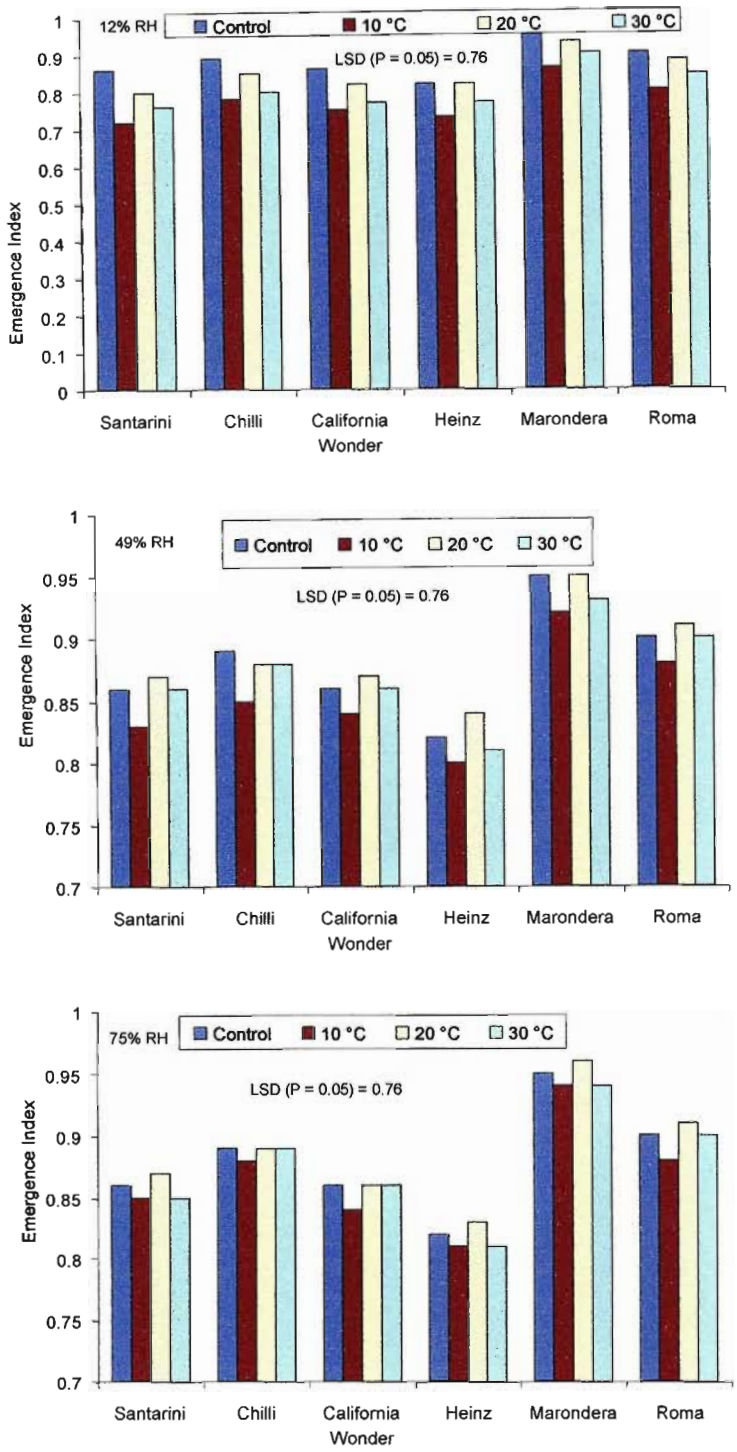

Figure 3.3. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera', 'Roma') seedling emergence index in response to imbibition temperatures (inset) and dehydration relative humidities (12%, 49% and 75% RH).

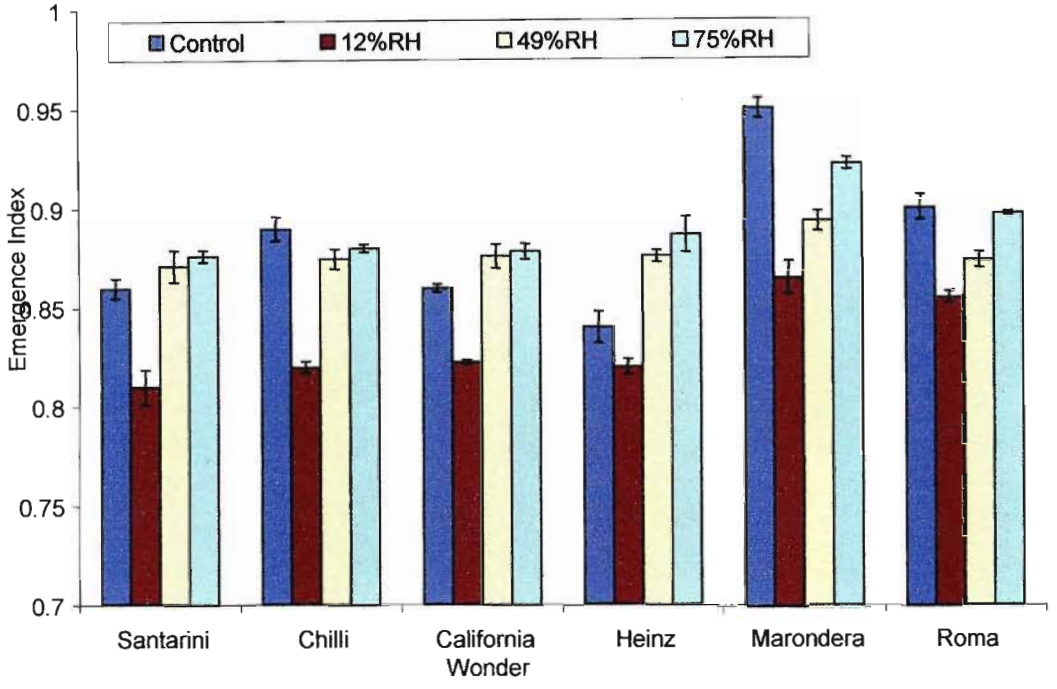

Figure 3.4. Effect of seed dehydration relative humidities on seedling emergence of pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma'). Note: LSD (P=0.05) =0.07. Control seeds were not hydrated.

3.3.2 Pre-transplanting seedling growth

Plant growth was determined by seedling height, leaf number and seedling shoot mass (Figures 3.5, 3.6 and 3.7).

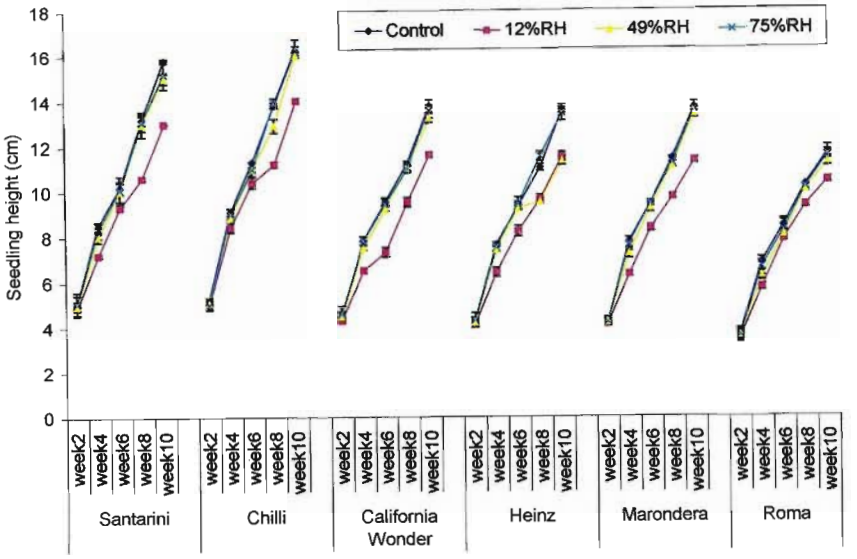

Figure 3.5. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') seedling height from two weeks after sowing in response to seed dehydration at different relative humidities (inset). Note: LSD (P=0.05) =3.2. Control seeds were not hydrated.

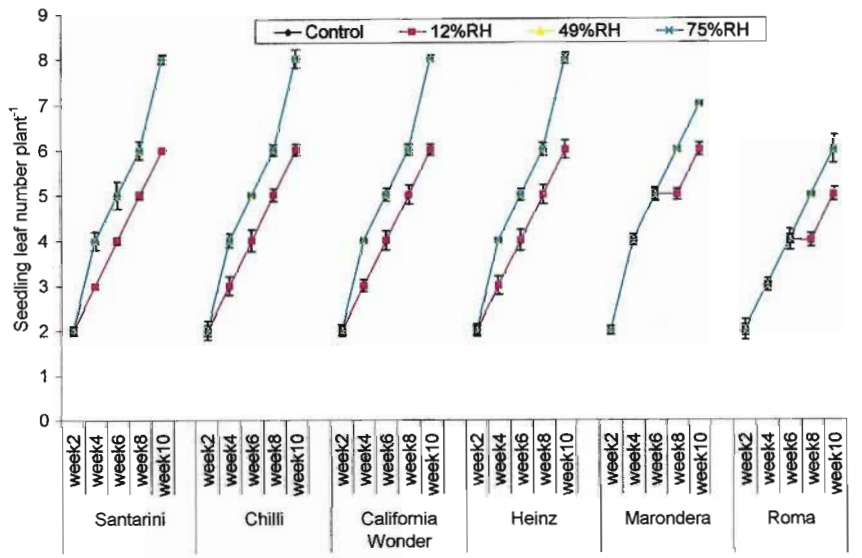

Figure 3.6. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and Roma') seedling leaf number from two weeks after sowing in response to seed dehydration at different relative humidities (inset). Note: LSD (P=0.05) = 0.5. Control seeds were neither hydrated nor dehydrated.

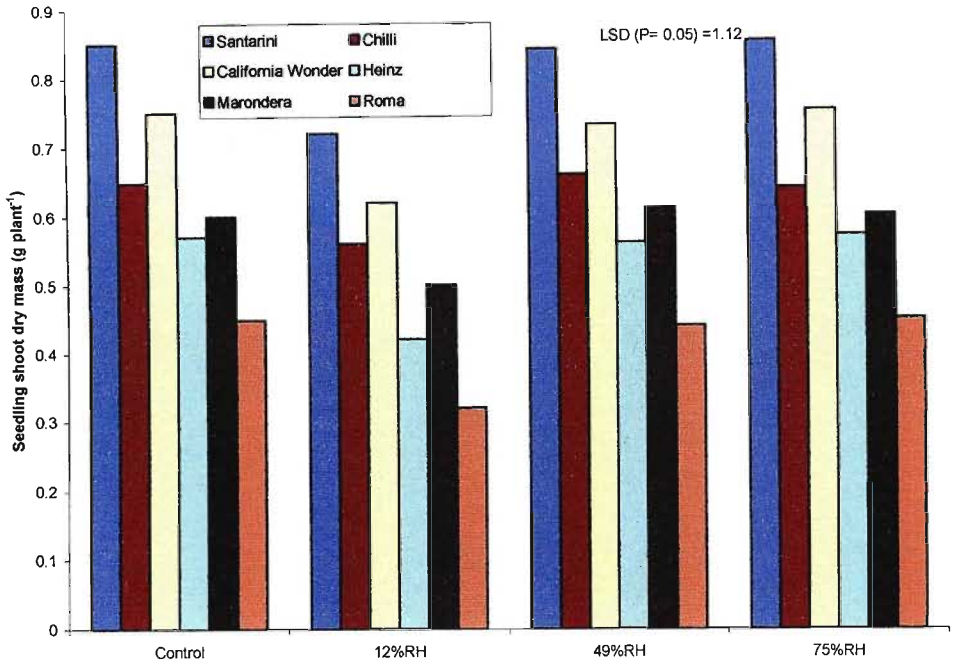

Figure 3.7. Effect of seed dehydration relative humidity on seedling shoot dry mass in pepper cultivars, Chilli and tomato cultivars. Control seeds were not hydrated.

Cultivars differed significantly ($P < 0.05$) (Appendix 3.2C, D and E) in seedling height, leaf number and shoot dry mass across all relative humidity treatments (Figures 3.4 to 3.6). There was no significant effect of imbibition temperatures on seedling development. The differences between cultivars are likely associated with the genetic differences, and not the treatment effects. For all cultivars, 12% RH slowed seedling growth by delaying stem elongation and accumulation of leaves (Figures 3.5 and 3.6). The effect of delayed stem elongation and leaf accumulation resulted in decreased seedling shoot mass, determined 12 weeks after sowing (week 10) (Figure 3.6). Increasing the dehydration RH to 49% and 75% had no effect of seedling growth (Figures 3.5 and 3.6).

Although there were no differences between seedling sizes at the beginning of emergence test (two weeks after sowing) (Figure 3.8), the differences in height, leaf number and size, due to rapid seed dehydration, were visibly evident on the fourth week after sowing (Figure 3.8). Retardation of seedling development could

have negative consequences for nursery production in that seedlings could occupy space for a longer period of time, while there is a cost to the producer in maintenance. This study shows that rapid seed dehydration (12% RH) causes stress and could reduce seedling size by ~10 to 20% (Figure 3.6). The resulting seedlings may be too small for good plant performance after transplanting. Modi (2005) showed that dehydration RH for seeds could cause a delay in attainment of mature seedlings by three to seven days.

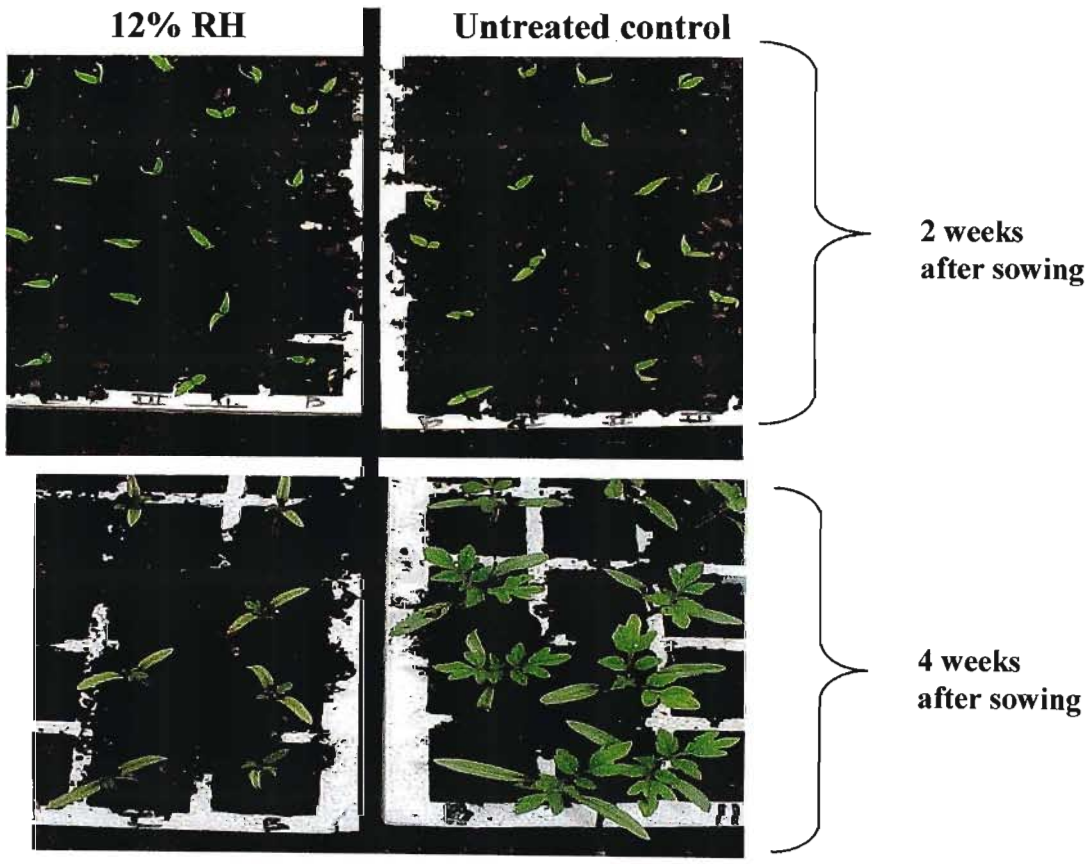

Figure 3.8. Effect of rapid dehydration (12% RH) on tomato seedling growth. The effect was similar for all pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma'). Control seeds were not hydrated.

The effect of rapid seed dehydration of pepper and tomato cultivars persisted until 12 weeks after sowing, when the seedlings were ready to be transplanted (week 10, Figures 3.5, 3.6 and Figure 3.9).

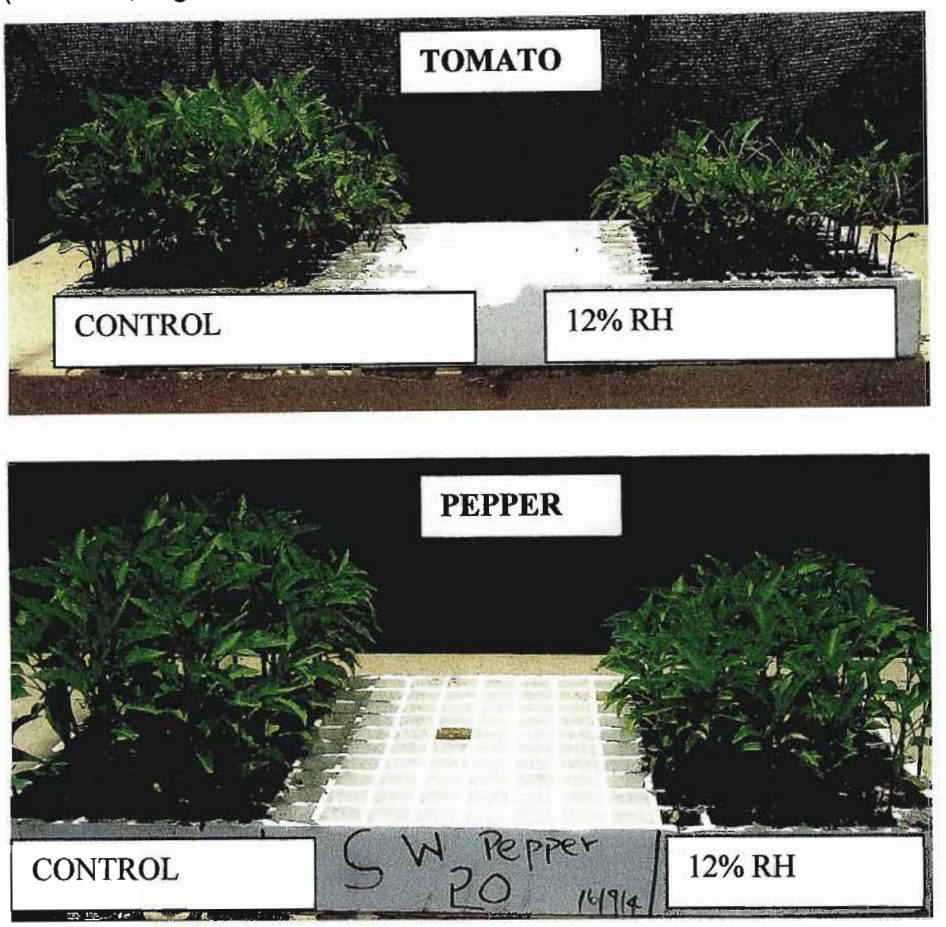

Figure 3.9. Effect of rapid dehydration (12% RH) on mature tomato ('Heinz', 'Marondera' and 'Roma'), pepper ('Santarini' and 'California Wonder') and Chilli seedlings. Control seeds were not hydrated.

3.3.3 Post-transplanting growth and yield

Taking into account the pre-transplanting growth curves, the growth of pepper and tomato cultivars followed the normal sigmoidal curve for annual plants (Salisbury and Ross, 1992). Plant growth was determined for eight weeks after transplanting, and there were significant ($P < 0.05$) differences between dehydration treatments, but no effect of imbibition temperatures was found (Figure 3.10). There was a significant ($P < 0.05$) effect of dehydration RH on

plant growth, however, the effect was due to an interaction between cultivar and stage of growth (Figure 3.10). With the exception of 'Santarini', which showed no significant effect of RH, throughout its growth, rapid dehydration was found in all the other five cultivars (Figure 3.10). As was found during pre-transplanting, 'Santarini' and Chilli showed a significantly ($P < 0.01$) better growth than the other cultivars, however, this difference was likely due to genetic cultivar differences.

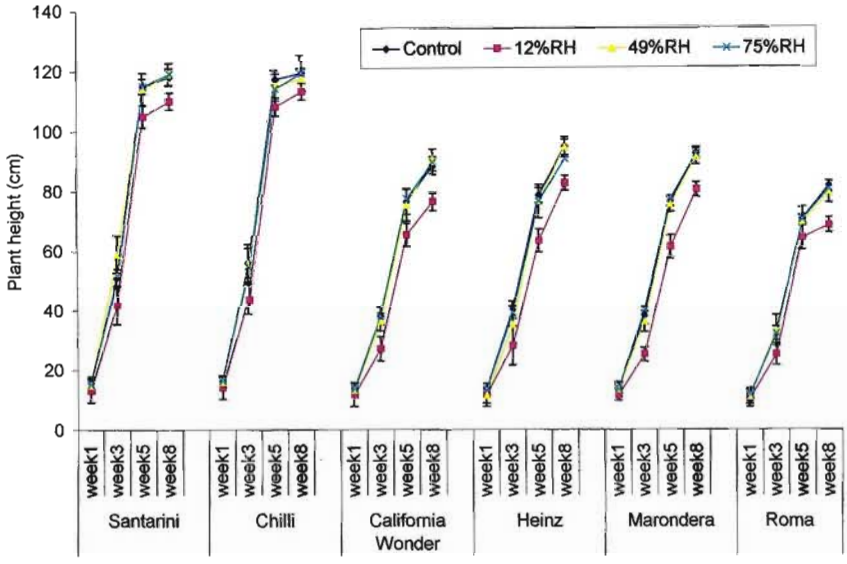

Figure 3.10. Growth of pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') plants after transplanting in response to seed dehydration relative humidities (inset). Control seeds were not hydrated.

At harvest maturity, there was a significant difference between cultivars, with respect to yield, fruit number and fruit mass (Figures 3.11 and 3.12). Expectedly, Chilli produced the highest number of fruits compared to the other Capsicum species, and compared to tomato cultivars (Figure 3.11). Among the tomatoes, 'Roma' produced the highest number of fruits (Figure 3.11). The large fruit-sized green- and sweet-peppers ('Santarini' and 'California Wonder') produced fewer fruits, so did the large fruit-sized tomatoes ('Heinz' and 'Marondera'). Clearly, the

differences between cultivars, with respect to fruit numbers, were not due to treatment effects.

There was an expected negative correlation to fruit numbers (Figures 3.11 and 3.12). Tomatoes produced greater fruit mass than peppers, and for both species, the larger the fruit number, the smaller was the fruit mass (Figures 3.11 and 3.12).

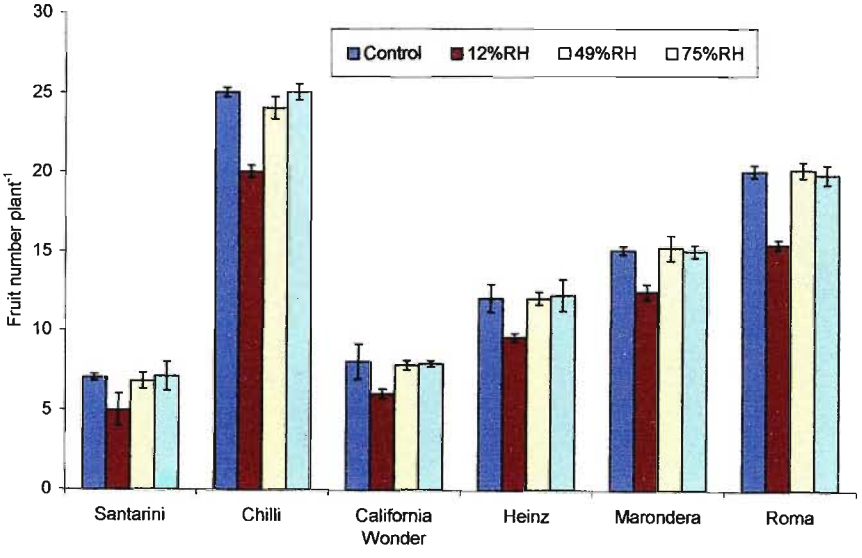

Figure 3.11. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') fruit numbers in response to seed dehydration relative humidity (inset). Control seeds were not hydrated.

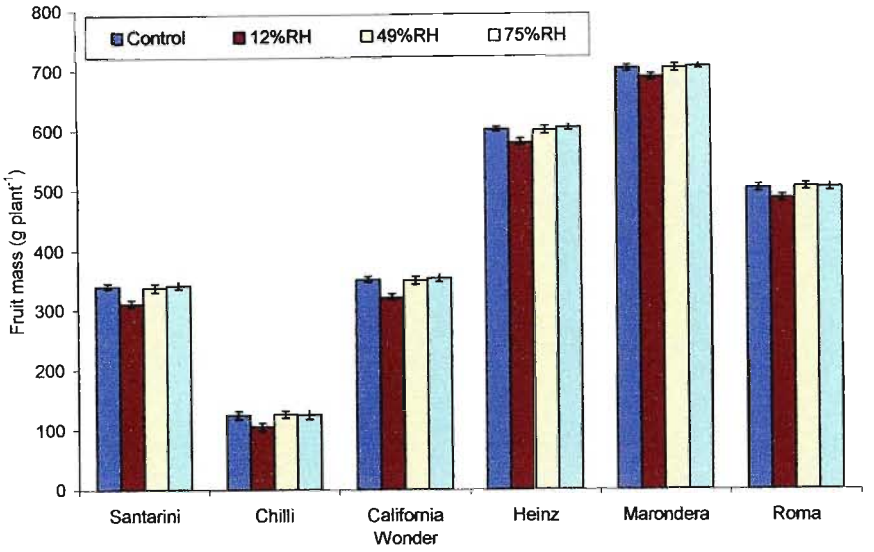

Figure 3.12. Pepper ('Santarini' and 'California Wonder'), Chilli and tomato ('Heinz', 'Marondera' and 'Roma') yield in response to seed dehydration relative humidity (inset). Control seeds were not.

Rapid seed dehydration (12% RH) caused a significant reduction in fruit yield, regardless of species (Figure 3.13). However, there was no significant effect of seed imbibition temperature.

This study confirmed previous findings by Modi (2005) that rapid seed dehydration reduces seedling emergence and growth before transplanting. That study, however, examined one pepper cultivar ('California Wonder'). In the present study, three pepper cultivars and three tomato cultivars showed consistent responses (negative effect) to rapid seed dehydration. Moreover, the present study showed that the effect of rapid dehydration can persist through plant development to affect final yield.

It is generally assumed that seed germination is related to seedling emergence, as confirmed by Baalbaki and Copeland (1987), but many researchers/scientists were not able to produce consistent correlations (Duczmal and Minicka, 1989; Egli and TeKrony, 1995; 1977; Kulik and Yaklich, 1982). Low temperature

imbibition has been shown to cause poor seedling emergence due to imbibitional injury. In this study, low imbibition temperatures (10°C) were shown to reduce seedling emergence, but the effect of low temperatures did not persist to be evident during seedling growth and yield.

Expensive F1 hybrid seeds are used in greenhouse tomato and pepper production. Therefore, growers and companies producing vegetable seedlings are interested in rapid and healthy seedling emergence, uniformity in seedling size and appearance, and resistance to unfavorable environmental conditions. Yield and quality of the final plants for short season vegetable crops such as tomato, pepper, lettuce, onion and cabbage is mostly affected by emergence (TeKrony and Egli, 1991). An adequate stand establishment as well as rapid and uniform seedling emergence are ensured by high quality seedlots (TeKrony and Egli, 1991). In this study, it was shown that good quality seed can easily be negatively affected by stress that imparts membrane integrity (imbibitional injury caused by low temperatures and rapid water loss after imbibition). Although priming is known for enhancing seed performance (germination) and increasing seed tolerance to stress such as lack of water and adverse temperatures, it has been shown to also reduce seedling emergence and germination time (TeKrony and Egli, 1991). In this study, the dehydration treatments that mimicked priming (e.g. dehydration at 75% RH left a significant amount of water in the seed: Figure 2.1) minimised the negative effects of low temperature imbibition on seedling emergence, and growth.

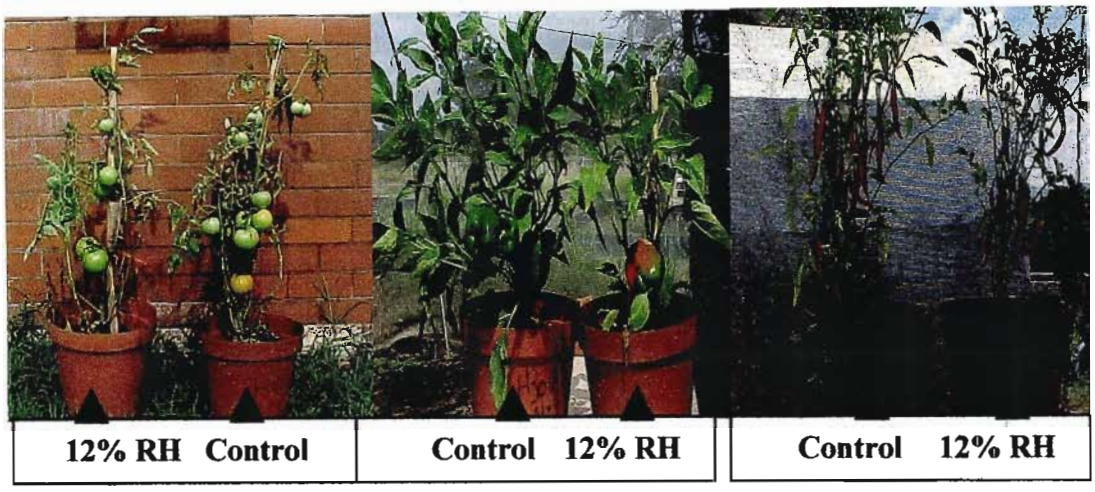

Figure 3.13. Comparison of mature tomato, Chilli and pepper plants for the effect of rapid seed dehydration on crop yield. Control seeds were not hydrated.

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CHAPTER 4

STATISTICAL MODEL TO RELATE SEED LABORATORY PERFORMANCE AND SEEDLING ESTABLISHMENT

4.1 Introduction

Yield and monetary value of vegetable crops are directly influenced by the timing and uniformity of seedling emergence (Finch-Savage, 1995). Equations have been used to analyse and quantify germination as a function of time (Bradford 1990; 1995; 1990; Ni and Bradford, 1992; Toselli and Casenave, 2002; 2004). Some of these models either require many parameters which one cannot always assign biological significance to or they do not allow rapid prediction of the effect of changes in a particular factor (Toselli and Casenave, 2004). Seed quality accounts for much of the variation in seedling emergence (Finch-Savage and Phelps, 1993). Temperature and seed moisture content are among the environmental factors that influence germination.

The hydrotime model is among the rigorously tested models to describe germination as a function of seed water potentials and it can automatically generate germination time courses simply responding to changes in water potential during imbibition (Bradford 1990; 1995; Toselli and Casenave, 2004). Time to radicle emergence for imbibed seeds at a given temperature is proposed by the hydrotime model and is related to two parameters: Hydrotime (θ_H) which is constant to the seed population, and base potential (Ψ_b) that is variable among individuals in a population (Toselli and Casenave, 2004). The variation of the base potential among individuals explains the fact that not all seeds germinate simultaneously and can be quantified by the standard deviation. The hydrotime model has been shown to provide quantitative characterisation and prediction of germination response to water potentials of several species (Dahal and Bradford, 1994; Cheng and Bradford, 1999; Toselli and Casenave, 2002; 2003).

Threshold models such as thermal time (Garcia-Huidobro *et al.*, 1982) and hydrothermal time (Gummerson, 1986; Bradford *et al.*, 1993; Bradford, 1995) that were used to explain and describe the germination response of seeds to temperature and water potential have played a role in the understanding of seed behaviour. However, data collected under constant conditions were used to derive and test these particular models (Finch-Savage *et al.*, 2000). Both thermal and hydrothermal time models described carrot germination data collected under constant conditions (Finch-Savage *et al.*, 1998). However, when the same data collected under constant conditions was applied to variable conditions in the field, there was no accurate germination described by the models (Finch-Savage *et al.*, 2000). It was reported that thermal time underestimated the time to germination, whereas hydrothermal time overestimated the time to germination, except under moist conditions (Finch-Savage *et al.*, 2000).

No reports on models that relate to seed germination and seedling establishment. Hence, the objective of this study was to develop a statistical model to predict seedling establishment parameters (emergence percentage, emergence index, and seedling size) in relation to seed germination parameters (germination percentage, germination index and seedling size at the final germination count). The data described in Chapters 2 and 3 were used for deriving a statistical model based on linear regression and principal component analysis.

4.2 Materials and methods

4.2.1 Seed germination and seedling establishment

Seeds were germinated and seedlings were grown as explained in Chapters 2 and 3 (sections 2.2.4 and 3.1).

4.2.2 Statistical analysis and model development

Analysis of variance for seed germination and seedling establishment was performed (Appendices 2.1 and 3.2) to determine differences between imbibition and hydration treatments (section 2.1). For each of the pepper cultivars ('Santarini' and 'California Wonder') Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma') data for germination parameters (germination percentage (G%), germination index (GI), and seedling size at the final germination count (SDM) were subjected to linear regression to obtain β_0 (intercept) and β_1 (slope) of the regression. Principal component analysis (PCA) was performed using the S-matrix (variance- covariance matrix) (GenStat, Release 7.0, Rothamsted Experimental Station, UK). For the purposes of the study, the first principal component (PC1) was selected for a statistical model to predict emergence from germination. Selection of PC1 was based on the following criteria:

(1) The highest latent root, (2) Percentage variation > 50%, and (3) Absolute value vectors for all variables. Statistical t-test was used to construct confidence intervals (CI) for absolute means of PC1. Calibration scales were established from the confidence intervals. The summary of PCA analysis (latent roots, % variation, absolute vectors, PC values and PC1 scores) is presented in Appendix 4. These data were used to derive a statistical model to predict seedling emergence from germination percentage as follows:

$$\hat{Y}_{emergence} = \beta_0 + \beta_1 X_{germination} \quad \text{.....Equation 1}$$

Where: $\hat{Y}_{emergence}$ = predicted emergence

β_0 = intercept

β_1 = slope

$X_{germination}$ = Mean of absolute PC1 for germination of control or treated (imbibition temperature or dehydration RH).

Note that X could be PC1 for germination index, seedling dry mass or any other germination parameter. For the purposes of this study, $X_{germination}$ was elected,

because germination percentage is normally used as a measure of seed quality in seed marketing. Also, PC1 (germination) = f (G%, GI, SDM). Means of PC1 were obtained from principal component scores of each PC1 (Appendix 3) for each cultivar and seed treatment (temperature and RH) (Appendix 4).

4.3 Results and discussion

It was shown in Chapter 3 that there were significant ($P < 0.01$) differences between cultivars, with respect to emergence. In this study, using the model (equation 1) to predict seedling emergence from seed germination showed that the differences between cultivars were maintained. However, the model overestimated seedling emergence by ca. 2 to 3%, for all cultivars, irrespective of seed treatment (Figures 4.1 to 4.4). There were expected significant differences between Equation 1 was used to predict emergence of each cultivar from germination percent. From Figure 4.4 low imbibition temperature (10°C) and low seed dehydration relative humidity (12% RH) were the only conditions used because they were the only treatments that showed differences (significant effects).

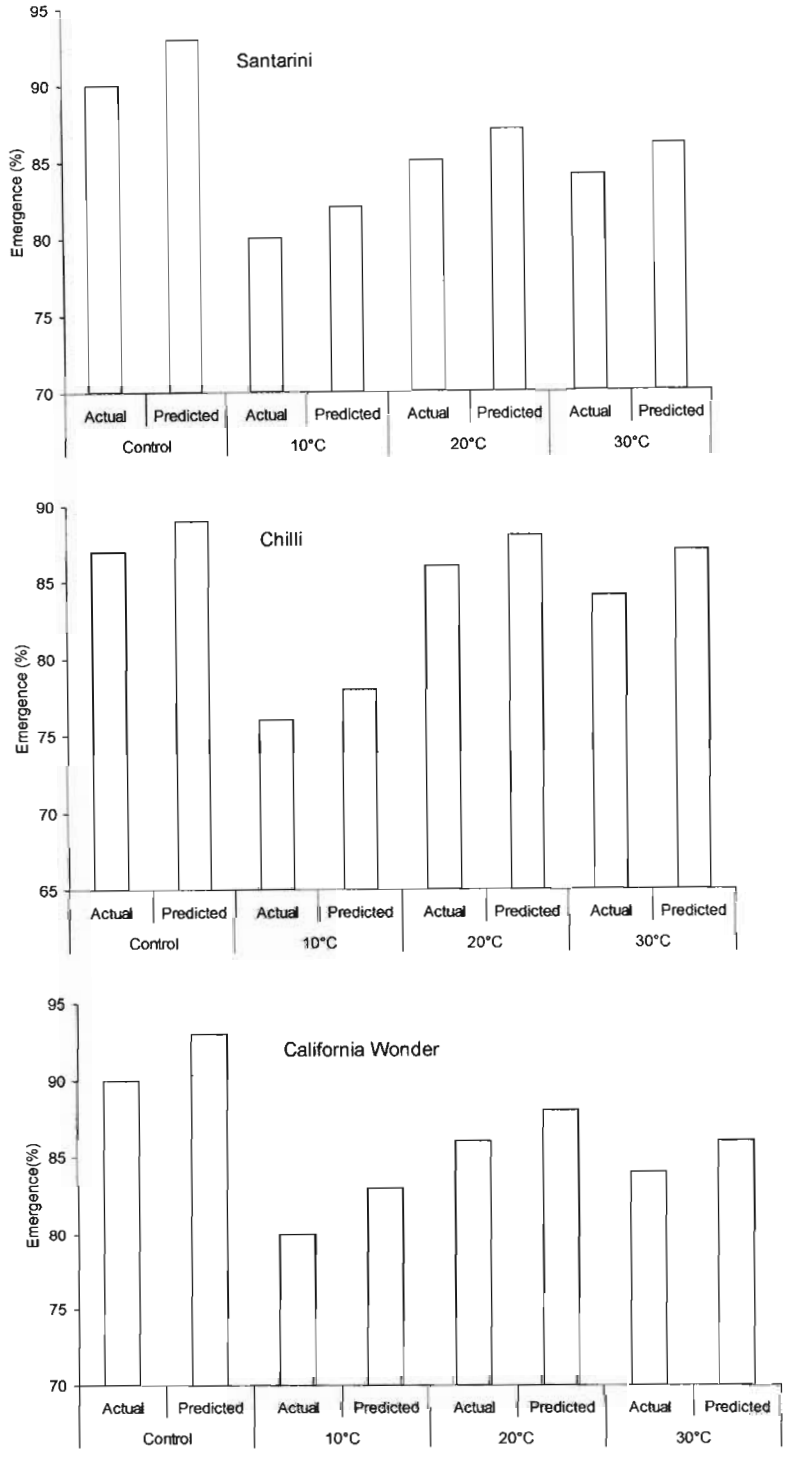

Figure 4.1. Comparison of actual seedling emergence and predicted seedling emergence using equation 1 for pepper cultivars ('Santarini' and 'California Wonder') and Chilli in response to seed imbibition temperatures. Control seeds were not hydrated.

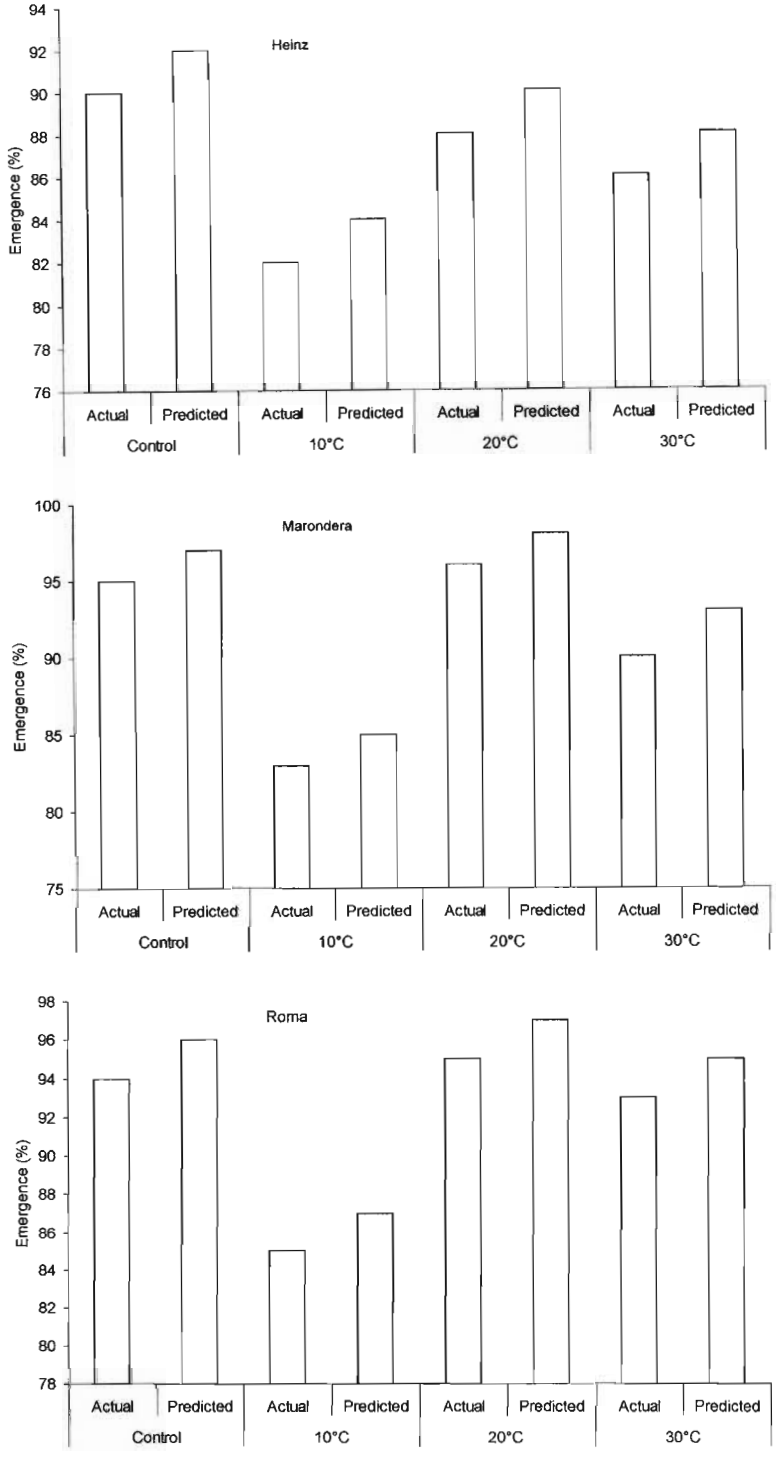

Figure 4.2. Comparison of actual seedling emergence and predicted seedling emergence using equation 1 for tomato cultivars ('Heinz', 'Marondera' and 'Roma') in response to seed imbibition temperatures. Control seeds were not hydrated.

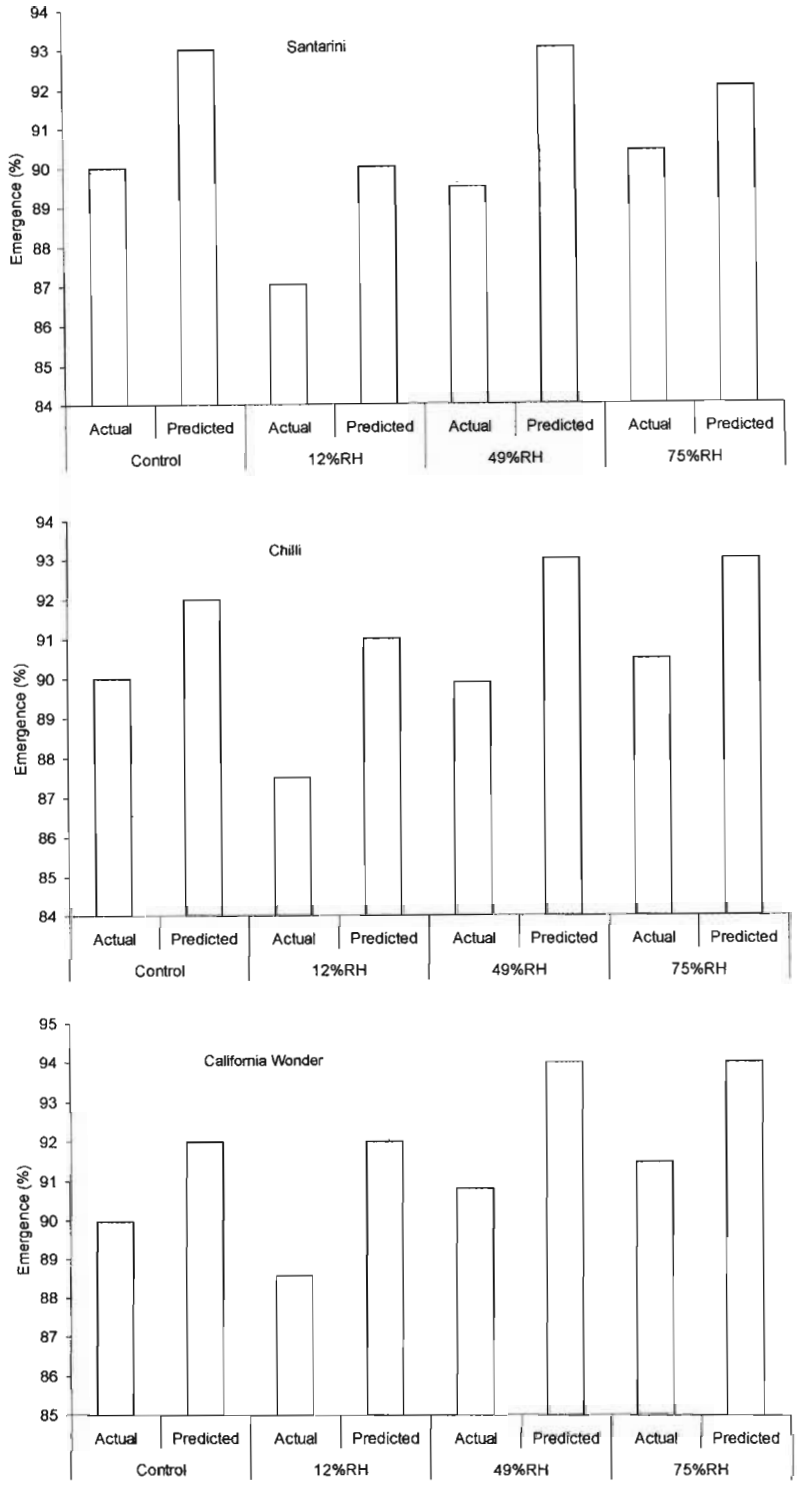

Figure 4.3. Comparison of actual seedling emergence and predicted seedling emergence using equation 1 for pepper cultivars ('Santarini' and 'California Wonder') and Chilli in response to seed dehydration relative humidity. Control seeds were not hydrated.

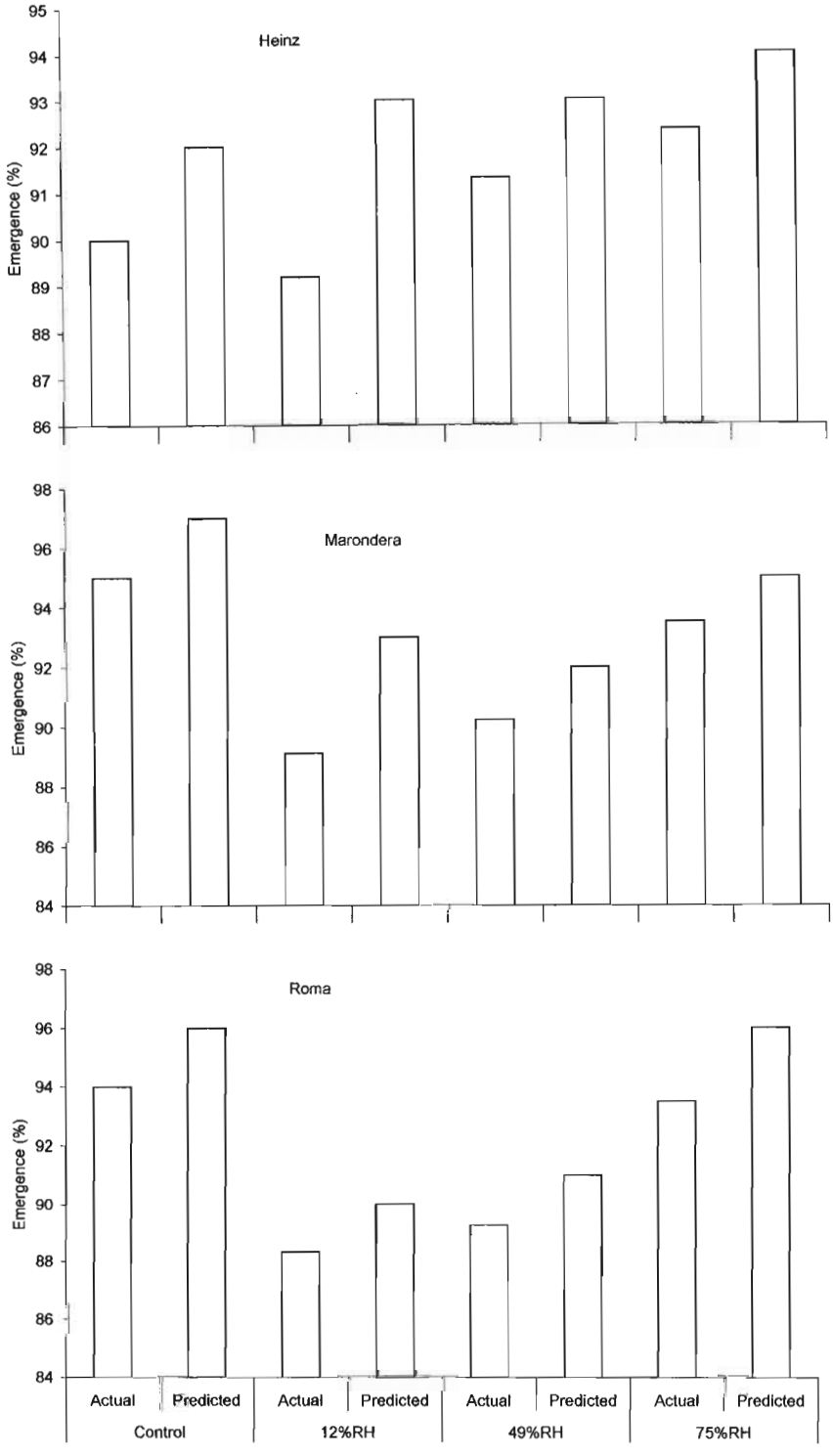

Figure 4.4. Comparison of actual seedling emergence and predicted seedling emergence using equation 1 for tomato cultivars ('Heinz', 'Marondera' and 'Roma') in response to seed dehydration relative humidity. Control seeds were not hydrated.

The variances between actual and predicted emergence observed in Figures 4.1 to 4.4 were not surprising, judging by previous observations for seed performance models (Bradford *et al.*, 1993; Finch-Savage and Phelps, 1993; Finch-Savage *et al.*, 1998). Finch-Savage *et al.* (1998) showed that thermal and hydrothermal time adequately described carrot germination data collected under constant conditions. However, when the model was applied to data collected under variable conditions in the field, accuracy was significantly reduced (Finch-Savage *et al.* 2000). The thermal time model consistently underestimated the time to germination, whereas the hydrothermal time model overestimated the time to germination (Finch-Savage *et al.* 2000).

Although it is evident from Figures 4.1 to 4.4 that there is a correlation between actual and predicted emergence using equation 1, it was of interest to perform a regression analysis to illustrate the relationships in response to imbibition temperature and dehydration RH treatments. Linear regression lines of actual and predicted seedling emergence for all cultivars were consistence in (Figure 4.50. The model used in this study to predict seedling emergence from seed germination is significantly reliable. The reliability is indicated by the high amount of emergence behaviour explained by seed germination as shown by high values of R^2. Selection of the treatments that had a negative effect on germination and emergence for Figure 4.5 was because both low imbibition temperature and rapid dehydration had been shown to be stressful for seeds (Chapters 2 and 3). Data in Figures 4.5 indicate that the model was reliable even in the presence of stress on seeds.

Correlation between seedling emergence and seed treatment has been previously explained. Finch-Savage and Phelps (1993) showed that onion seedling emergence can be explained by the influence of soil temperature and soil water potential. Although the present study did not use soil temperature, there is a similarity between the soil temperature treatment used by Finch-

Savage *et al.* (2000) and imbibition temperature. The objective of using temperature treatments in the present study was to mimic field/nursery conditions that might prevail when seedlings absorb water during the initial stages of germination. It is concluded that seedling emergence can be predicted from seed germination, and the model presented in equation 1 can be used for this purpose.

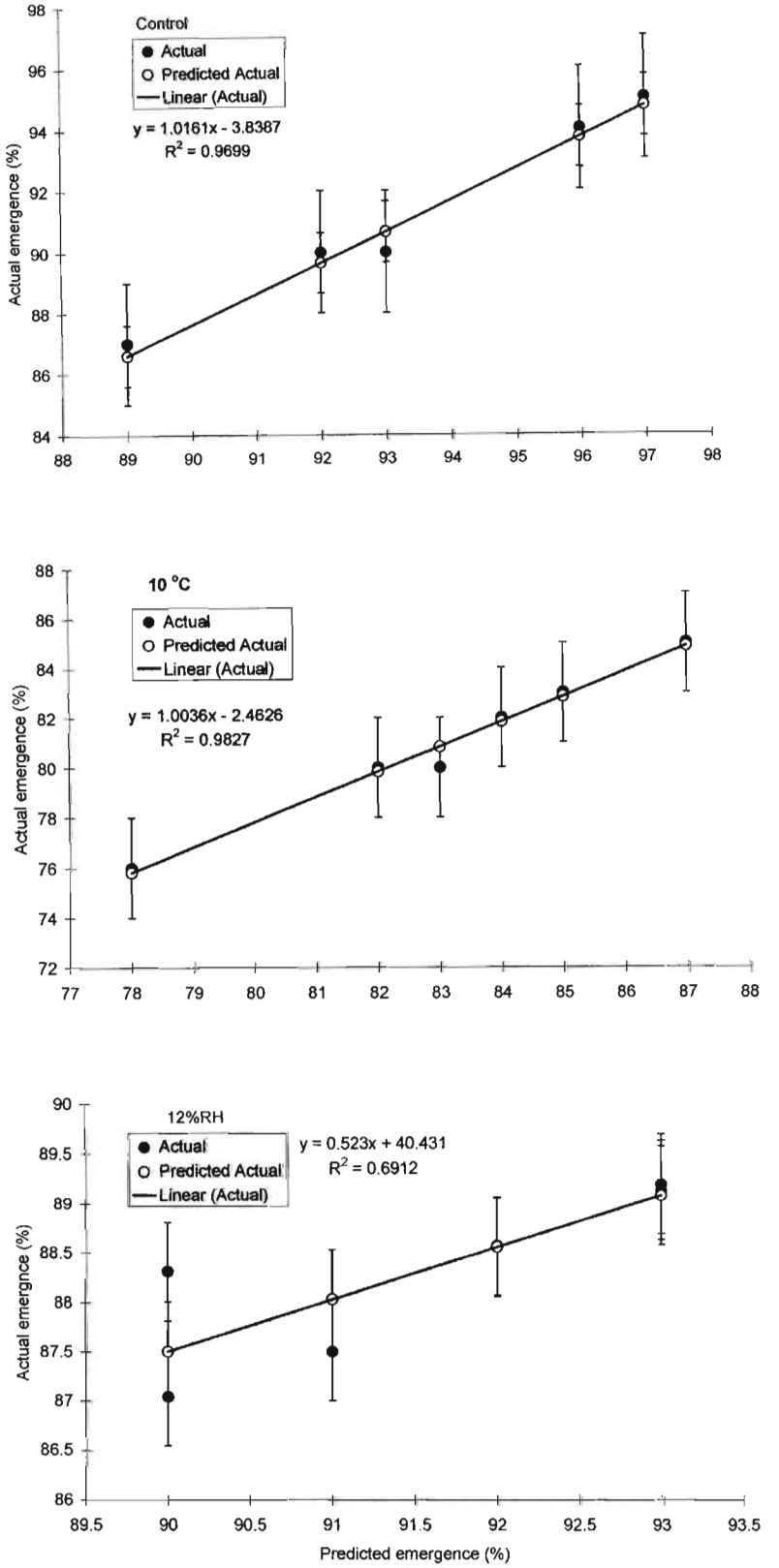

Figure 4.5. Actual emergence of all cultivars and predictions using equation 1.

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CHAPTER 5

GENERAL DISCUSSION AND CONCLUSIONS

Commonly used stress tests to determine seed vigour are cold tests, accelerated aging and conductivity tests. These seed vigour tests are generally used for large-seeded species, and are not reliable for small-seeded species, such as vegetables. This study was undertaken on the premise from a previous study by Modi (2005) that seed desiccation using low relative humidity causes stress on peeper seeds. In that study, the stress effect was indicated by leakage of mineral elements in response to desiccation. Consequently, it was proposed in this study that desiccating seeds using saturated salts would be detrimental to seed performance (germination and vigour) and seedling establishment after emergence. In this study, seed stress was determined indirectly by electrical conductivity. Although there was a significant increase in electrical conductivity of steep water derived from seeds that were subjected to desiccation stress, this study cannot conclude that seed stress was directly measured. However, it can be assumed that an increase in conductivity, an indication of electrolyte leakage is associated with stress on cell membranes of the affected seeds as was confirmed by Modi (2005).

To expand on the study by Modi (2005) this study investigated the effect of imbibition temperature on seed performance and seedling establishment. It was found that imbibition of tomato and pepper seeds at temperatures ranging from 10°C to 30°C increased seed water content during imbibition to approximately 50% in two hours, irrespective of imbibition temperature. In this study, the change in seed mass (~ 49%) due to water absorption was used to indicate water uptake, according to the Association of Official Seed Analysts (1983). The increase in mass was in agreement with previous findings in pepper (Modi, 2005), and it was not significantly influenced by species. Although there was no significant difference between temperatures dehydration of tomato and pepper

cultivars, seed water loss was significantly affected by dehydration relative humidity. The desiccation effects of saturated salts showed that low relative humidity (12% RH) rapidly reduced the seed moisture content to about 2% above the original moisture content, whereas the higher relative humidities, 49% and 75% RH, maintained seed moisture content at about 10% and 15% above the pre-imbibition moisture content, respectively.

This study showed that low imbibition temperature (10°C) significantly damaged seed membrane integrity, which was shown by excessive leakage of soluble solids out of seeds during imbibition. This finding suggests that tomato and pepper seeds are sensitive to imbibitional injury at low temperatures. Imbibitional injury was also found to have a similar effect to rapid dehydration caused by drying seeds at 12% RH. The ability of seeds to tolerate the effects of cold imbibition and rapid desiccation was determined by seed performance during germination, seedling emergence and seedling growth. The negative effects of imbibitional injury and rapid dehydration were observed in poor seed performance during germination and during seedling establishment and seedling growth. Seeds that had been subjected to 10°C imbibition temperature and/or 12% RH consistently displayed a low total germination percentage, a low germination index, a low seedling emergence, low emergence index, smaller seedlings and eventually lower fruit yields compared with seeds that were not subjected to imbibition or dehydration. These findings emphasize the significant effects of low imbibition temperature and rapid dehydration as inducers of low quality in pepper and tomato seeds. It is important to note that the differences between tomato species, with respect to seedling growth may have been due to the different features of growth for the species studied (Salisbury and Ross, 1992), and not treatment effects. For example, that 'Roma' tomato showed slow growth compared with 'Heinz' and 'Marondera' may have been due to the former being determinate whereas the latter are indeterminate. The effect of seedling etiolation, also affected determination of seedling height. It is recommended that future studies quantify these effects (determinate and indeterminate growth and

etiolation) to avoid possible blurring of treatment effects when seedling growth is an important determination of treatment effects.

The findings of this study on imbibitional injury and rapid dehydration agree with previous studies (Nijsse *et al.*, 2004; Hoekstra *et al.*, 1999). Occurrence of imbibitional injury in multicellular organisms was explained by Nijsse *et al.*, 2004. Seed cell walls are known to be highly curved in the dry state, and their rehydration requires coordinated cellular imbibition and cell wall unfolding (Bradford, 2004). If one cell rehydrates faster than its neighbours, the effect causes a forced stretching of still highly viscous membranes, walls and cytoplasm, resulting in substantial tension. To avoid cell-to-cell friction, imbibition of the embryo should occur sufficiently slowly to accommodate a homogenous swelling. However, a thick-walled surrounding layer, such as the endosperm in tomato and pepper seeds, can act as a barrier for too rapid water influx (Bradford, 2004). Alternatively, cell wall injury and tissue rupture are the result of non-homogenous swelling of tissues, leading to tension cracks within the cell walls (Nijsse *et al.*, 2004; Hoekstra *et al.*, 1999). It can be assumed that if imbibitional injury occurs in seeds, the natural barriers have been compromised by some stress factor. In the present study, low imbibition temperature (10°C) and rapid dehydration (12% RH) might have damaged the seed's natural barrier to injury during the early stages of germination (Bradford, 2004, Bewley and Black, 2000). Hence the reduction in seed performance (germination percentage and germination index), accompanied by an increase in electrical conductivity, and reduction in seedling performance in response to 10 °C and 12% RH treatments.

The statistical model used in this study showed that it is possible to predict seedling establishment from seed germination, although the predicted values were higher than the actual seedling emergence values. The consistency with which actual emergence and predicted emergence occurred suggested that the model was reliable. This finding is important for the seed industry and the

nurseries, because the quality of seed merchandise is generally determined by seed germination percentage. Therefore, the number and quality of seedlings produced from a seedlot are expected to be closely correlated to the germination percentage indicated on the seedlot packaging material. That there was also a correlation between seed germination and seedling establishment in situations where seeds were subjected to low imbibition temperature and rapid dehydration stresses is an indication that the model is robust and can be relied upon under a wide range of conditions. This finding is important because seeds can be subjected to any kind of stress during handling, transport, storage, planting and in seedling trays or seedbeds prior to imbibition. Although this study did not simulate all the possible stress factors affecting seed quality, it is believed that the low imbibition and rapid dehydration stresses are useful because they are simple, rapid and can be repeated. These characteristics are ideal for a reliable seed vigour test.

Most growers and seed companies aim to produce high quality seeds that will produce healthy seedlings. This study showed that even good quality seed can easily be negatively affected by stress that imparts membrane integrity (imbibitional injury caused by low temperatures and rapid water loss after imbibition). Although priming is known for enhancing seed performance (germination) and increasing seed tolerance to stress such as lack of water and adverse temperatures, it has been shown to also reduce seedling emergence and germination time (TeKrony and Egli, 1991). In this study, the dehydration treatments that mimicked priming (e.g. dehydration at 75% RH) left a significant amount of water in the seed (Figure 2.1) and minimised the negative effects of low temperature imbibition on seedling emergence and growth.

In conclusion, this study provided evidence to confirm the previous finding (Modi, 2005) that dehydrating seeds at 12% RH followed imbibition reduces seed performance. Whereas Modi (2005) showed the effect of rapid dehydration on one pepper cultivar ('California Wonder'), the present study showed a consistent

response to rapid seed dehydration by pepper cultivars ('Santarini' and 'California Wonder'), Chilli and three tomato cultivars ('Heinz', 'Marondera' and 'Roma'). The statistical model produced in this study agreed with the mathematical model produced by Modi (2005) in relating the effect of stress on seeds (desiccation) and seedling establishment. However, it is recommended that the "Modi-model" is compared to the statistical model from this study in determining seed quality for a wider variety of species than tomatoes and peppers.

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APPENDIX 2.1 Analysis of variance for seed mass changes of pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma') during imbibition and dehydration period

A. Analysis of variance of Chilli seed mass change during imbibition and dehydration periods.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	1	0.008507	0.008507	1.74	
Rep.RH stratum					
RH	2	0.027699	0.013850	2.83	0.261
Residual	2	0.009792	0.004896	3.88	
Rep.RH.Time stratum					
Time	4	6.851195	1.712799	1358.24	<.001
RH.Time	8	0.017163	0.002145	1.70	0.196
Residual	12	0.015132	0.001261	0.54	
Rep.RH.Time.Temp stratum					
Temp	2	0.003095	0.001547	0.66	0.525
RH.Temp	4	0.032711	0.008178	3.48	0.019
Time.Temp	8	0.018508	0.002314	0.99	0.467
RH.Time.Temp	16	0.030066	0.001879	0.80	0.675
Residual	30	0.070448	0.002348		
Total	89	7.084317			

B. Analysis of variance of Santarini seed mass change during imbibition and dehydration periods.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	1	0.043209	0.043209	13.63	
Rep.RH stratum					
RH	2	0.036715	0.018357	5.79	0.147
Residual	2	0.006342	0.003171	0.14	
Rep.RH.Temp stratum					
Temp	2	0.005511	0.002755	0.12	0.885
RH.Temp	4	0.117605	0.029401	1.33	0.360
Residual	6	0.132882	0.022147	5.79	
Rep.RH.Temp.Time stratum					
Time	4	17.518790	4.379698	1145.80	<.001
RH.Time	8	0.155782	0.019473	5.09	<.001
Temp.Time	8	0.073479	0.009185	2.40	0.034
RH.Temp.Time	16	0.132068	0.008254	2.16	0.028
Residual	36	0.137606	0.003822		
Total	89	18.359990			

C. Analysis of variance of California Wonder seed mass change during imbibition and dehydration period.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	1	0.043209	0.043209	13.63	
Rep.RH stratum					
RH	2	0.036715	0.018357	5.79	0.147
Residual	2	0.006342	0.003171	0.14	
Rep.RH.Temp stratum					
Temp	2	0.005511	0.002755	0.12	0.885
RH.Temp	4	0.117605	0.029401	1.33	0.360
Residual	6	0.132882	0.022147	5.79	
Rep.RH.Temp.Time stratum					
Time	4	17.518790	4.379698	1145.80	<.001
RH.Time	8	0.155782	0.019473	5.09	<.001
Temp.Time	8	0.073479	0.009185	2.40	0.034
RH.Temp.Time	16	0.132068	0.008254	2.16	0.028
Residual	36	0.137606	0.003822		
Total	89	18.359990			

D. Analysis of variance of Marondera seed mass change during imbibition and dehydration period.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	1	0.028801	0.028801	3.85	
Rep.RH stratum					
RH	2	0.012233	0.006117	0.82	0.550
Residual	2	0.014952	0.007476	1.21	
Rep.RH.Time stratum					
Time	4	25.542723	6.385681	1033.21	<.001
RH.Time	8	0.021720	0.002715	0.44	0.875
Residual	12	0.074165	0.006180	1.06	
Rep.RH.Time.Temp stratum					
Temp	2	0.041962	0.020981	3.59	0.040
RH.Temp	4	0.011775	0.002944	0.50	0.733
Time.Temp	8	0.031565	0.003946	0.68	0.709
RH.Time.Temp	16	0.059484	0.003718	0.64	0.829
Residual	30	0.175216	0.005841		
Total	89	26.014596			

E. Analysis of variance of Roma seed mass change during imbibition and dehydration period.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	1	0.004594	0.004594	17.86	
Rep.RH stratum					
RH	2	0.012838	0.006419	24.96	0.039
Residual	2	0.000514	0.000257	0.15	
Rep.RH.Time stratum					
Time	4	2.055848	0.513962	290.86	<.001
RH.Time	8	0.009833	0.001229	0.70	0.690
Residual	12	0.021205	0.001767	0.55	
Rep.RH.Time.Temp stratum					
Temp	2	0.020797	0.010399	3.26	0.052
RH.Temp	4	0.006409	0.001602	0.50	0.734
Time.Temp	8	0.047249	0.005906	1.85	0.106
RH.Time.Temp	16	0.022210	0.001388	0.44	0.959
Residual	30	0.095674	0.003189		
Total	89	2.297171			

F. Analysis of variance of Heinz seed mass change during imbibition and dehydration period.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	1	0.007471	0.007471	25.11	
Rep.RH stratum					
RH	2	0.005453	0.002727	9.16	0.098
Residual	2	0.000595	0.000298	0.06	
Rep.RH.Temp stratum					
Temp	2	0.017574	0.008787	1.80	0.243
RH.Temp	4	0.006104	0.001526	0.31	0.859
Residual	6	0.029218	0.004870	0.80	
Rep.RH.Temp.Time stratum					
Time	4	1.897340	0.474335	78.27	<.001
RH.Time	8	0.023180	0.002898	0.48	0.863
Temp.Time	8	0.160170	0.020021	3.30	0.006
RH.Temp.Time	16	0.062760	0.003923	0.65	0.823
Residual	36	0.218159	0.006060		
Total	89	2.428024			

APPENDIX 2.2 Analysis of variance for pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma') seed performance characteristics under laboratory conditions.

A. Variate: Electrical conductivity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	1	556.4	556.4	0.60	
Rep.*Units* stratum					
Cultivar	5	631833.0	126366.6	136.50	<.001
RH	2	4264.9	2132.5	2.30	0.110
Temp	2	464.6	232.3	0.25	0.779
Cultivar.RH	10	25155.8	2515.6	2.72	0.009
Cultivar.Temp	10	43614.2	4361.4	4.71	<.001
RH.Temp	4	6095.2	1523.8	1.65	0.176
Cultivar.RH.Temp	20	36476.1	1823.8	1.97	0.026
Residual	53	49065.4	925.8		
Total	107	797525.5			

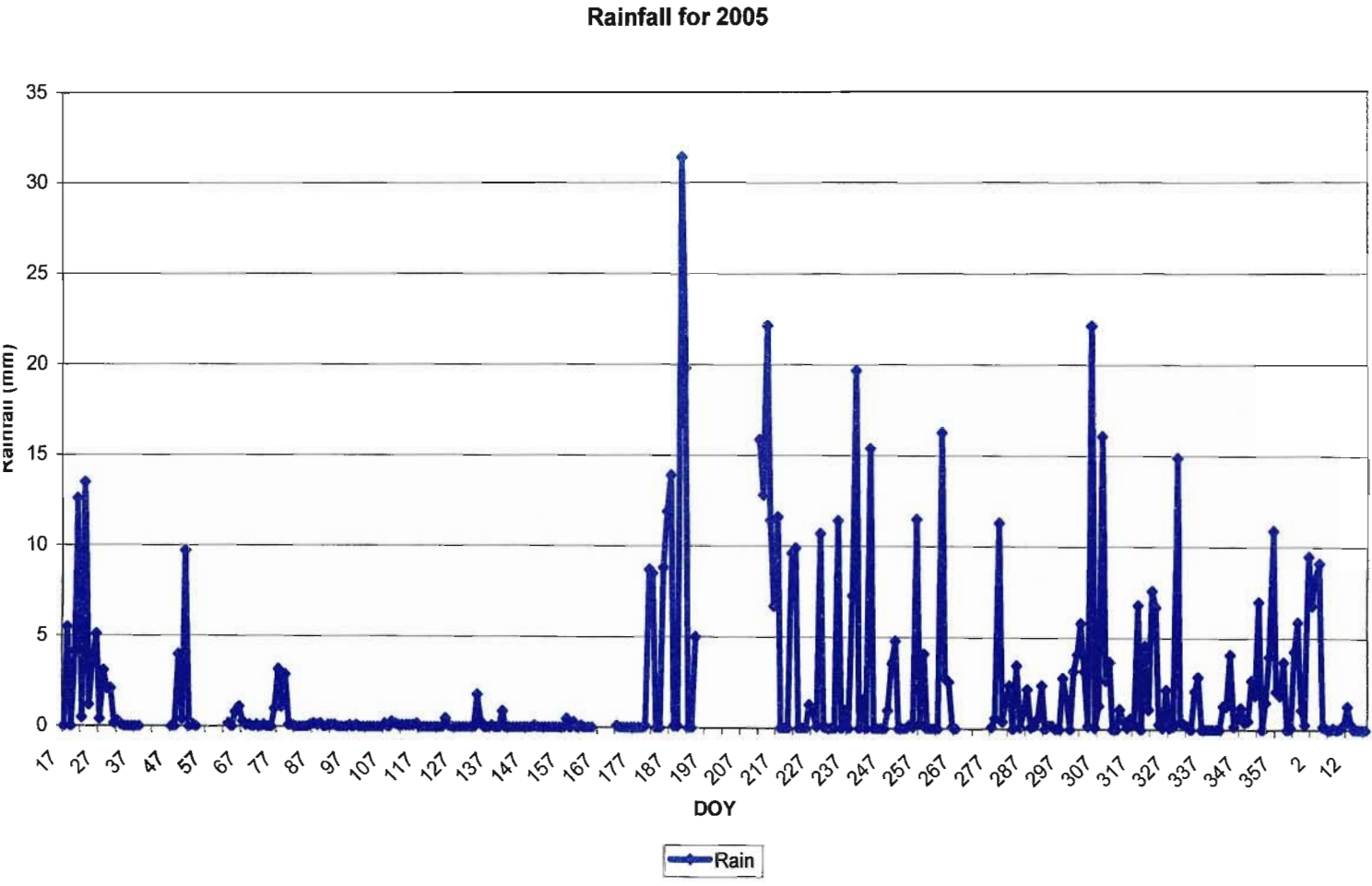
B. Variate: Total seed germination.

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	276.65	92.22	2.12	
Rep.Cultivar stratum					
Cultivar	5	1749.39	349.88	8.06	0.110
Residual	15	650.95	43.40	0.89	
Rep.Cultivar.*Units* stratum					
New_treat	1	1362.53	1362.53	27.96	0.101
Cultivar.New_treat	5	803.96	160.79	3.30	0.070
New_treat.RH	2	862.73	431.37	8.85	0.101
New_treat.Temperatures	2	403.01	201.50	4.14	0.172
Cultivar.New_treat.RH	10	1394.21	139.42	2.86	0.202
Cultivar.New_treat.Temperatures	10	1599.77	159.98	3.28	0.100
New_treat.RH.Temperatures	4	734.49	183.62	3.77	0.062
Cultivar.New_treat.RH.Temperatures	20	4250.23	212.51	4.36	0.110
Residual	210	10232.81	48.73		
Total	287	24320.75			

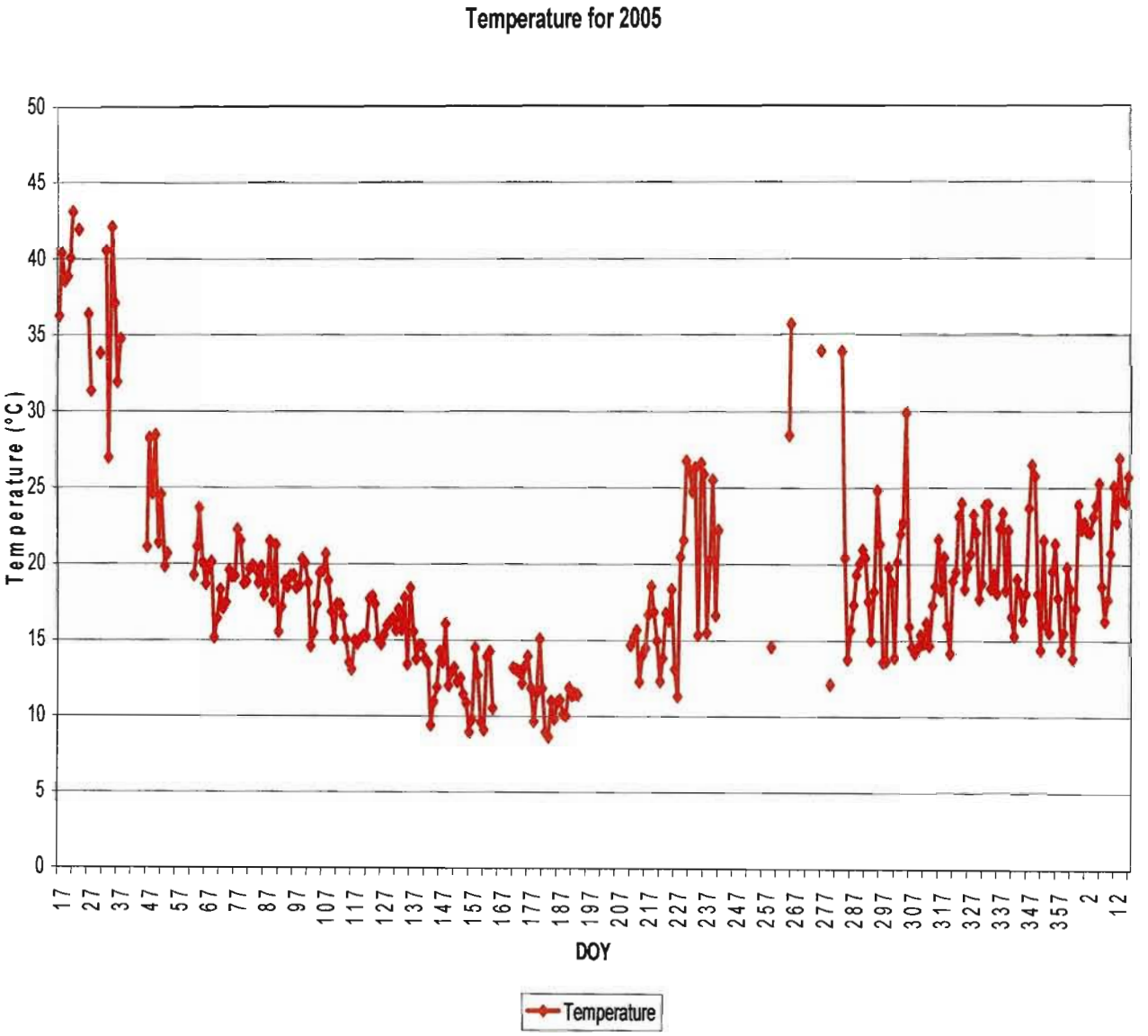
C. Variate: Germination index (GI).

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.021803	0.007268	1.75	
Rep.Cultivar stratum					
Cultivar	5	0.533521	0.106704	25.77	<.001
Residual	15	0.062121	0.004141	0.90	
Rep.Cultivar.*Units* stratum					
New_treat	1	0.135533	0.135533	29.48	<.001
Cultivar.New_treat	5	0.062659	0.012532	2.73	0.021
New_treat.RH	2	0.122676	0.061338	13.34	<.001
New_treat.Temperatures	2	0.045448	0.022724	4.94	0.008
Cultivar.New_treat.RH	10	0.059513	0.005951	1.29	0.235
Cultivar.New_treat.Temperatures	10	0.148794	0.014879	3.24	<.001
New_treat.RH.Temperatures	4	0.081522	0.020380	4.43	0.002
Cultivar.New_treat.RH.Temperatures	20	0.397837	0.019892	4.33	<.001
Residual	210	0.965330	0.004597		
Total	287	2.636756			

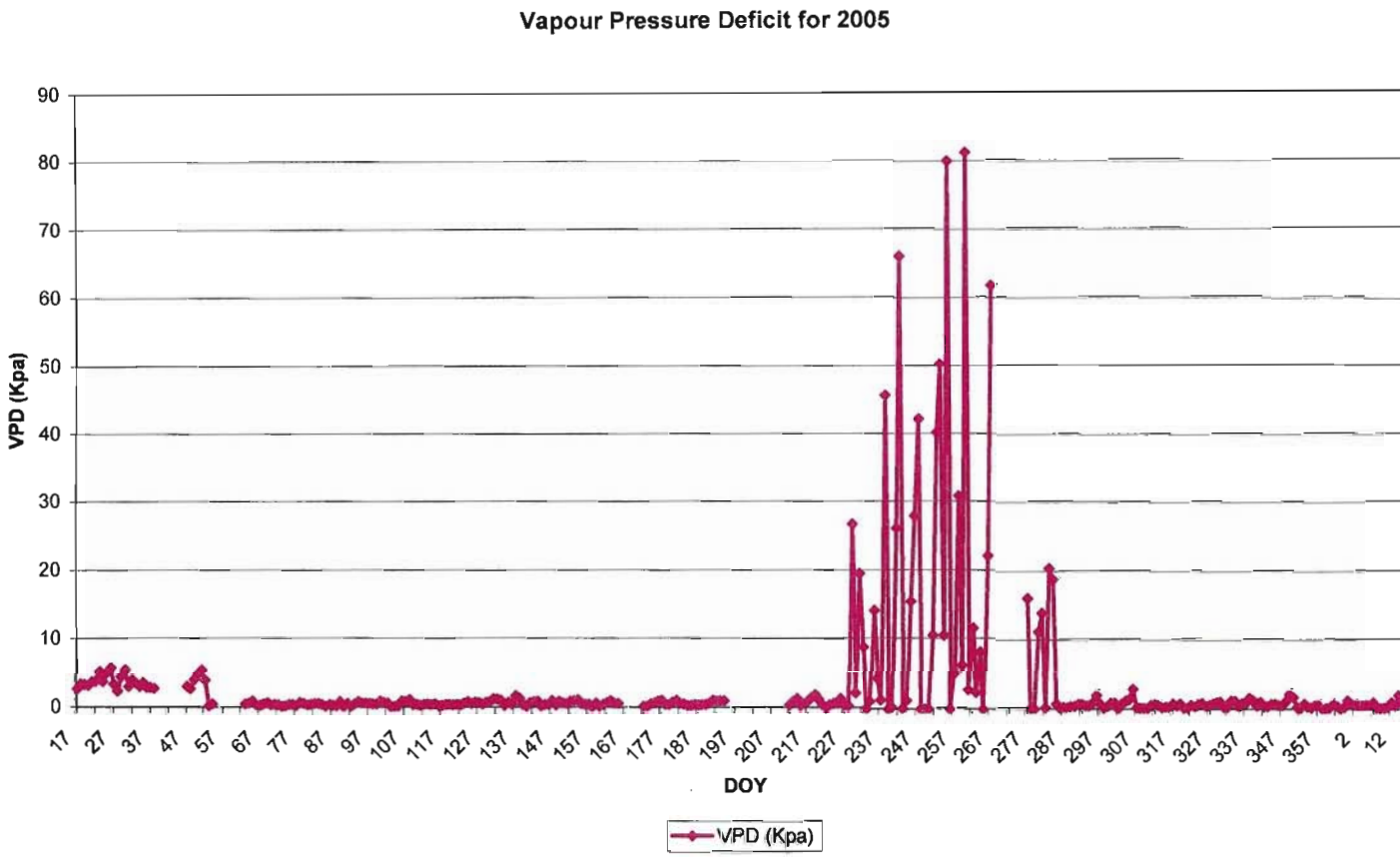
APPPENDIX 3.1 Climatic data at the site where seedlings were grown under shadehouse conditions. Note: DOY= day of the Year; the duration of the experiment covered the beginning to about 150th day. (Source CSIR).



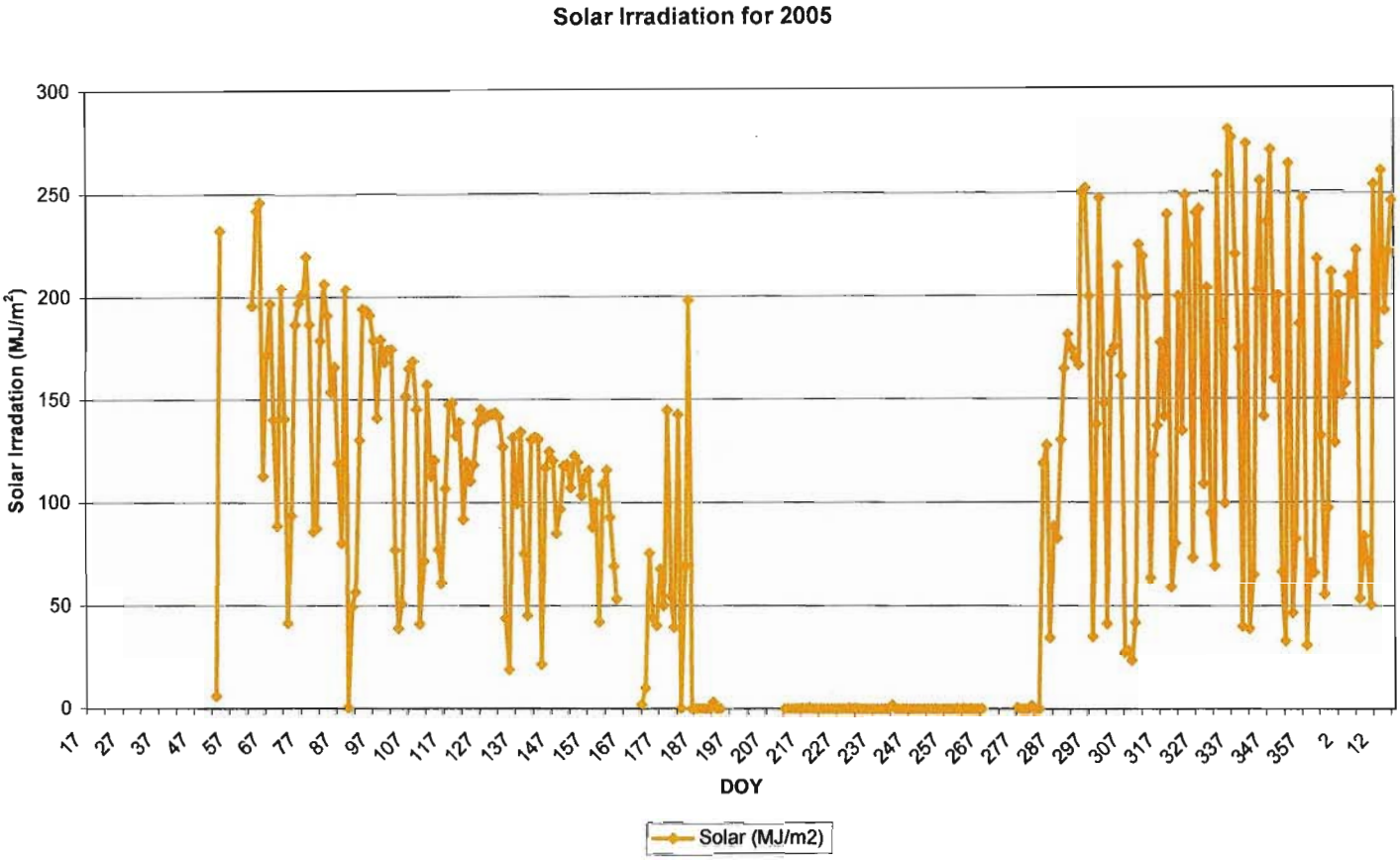
APPENDIX 3.1 continued....



APPENDIX 3.1 continued……



APPENDIX 3.1 continued....



APPENDIX 3.2 Analysis of variance for seedling emergence, seedling growth, plant growth and yield of pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma').

A. Variate: Emergence percentage

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1274.5	424.8	1.06	
Rep.Cultivar stratum					
Cultivar	5	117255.6	23451.1	58.27	<.001
Residual	15	6037.2	402.5	1.82	
Rep.Cultivar.*Units* stratum					
New_treatmets	1	2178.1	2178.1	9.84	0.002
Cultivar.New_treatmets	5	1218.4	243.7	1.10	0.361
New_treatmets.RH	2	91.6	45.8	0.21	0.013
New_treatmets.Temp	2	980.5	490.2	2.22	0.112
Cultivar.New_treatmets.RH	10	9224.0	922.4	4.17	<.001
Cultivar.New_treatmets.Temp	10	3351.5	335.2	1.51	0.136
New_treatmets.RH.Temp	4	390.4	97.6	0.44	0.001
Cultivar.New_treatmets.RH.Temp	20	9189.6	459.5	2.08	0.006
Residual	210	46461.3	221.2		
Total	287	197652.6			

B. Variate: Emergence index (EI)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.020824	0.006941	1.81	
Rep.Cultivar stratum					
Cultivar	5	1.659945	0.331989	86.64	<.001
Residual	15	0.057476	0.003832	1.07	
Rep.Cultivar.*Units* stratum					
New_treatmets	1	0.007050	0.007050	1.98	0.161
Cultivar.New_treatmets	5	0.022679	0.004536	1.27	0.277
New_treatmets.RH	2	0.002082	0.001041	0.29	0.747
New_treatmets.Temp	2	0.018778	0.009389	2.63	0.074
Cultivar.New_treatmets.RH	10	0.101466	0.010147	2.84	0.002
Cultivar.New_treatmets.Temp	10	0.025315	0.002531	0.71	0.715
New_treatmets.RH.Temp	4	0.016575	0.004144	1.16	0.029
Cultivar.New_treatmets.RH.Temp	20	0.119846	0.005992	1.68	0.038

Residual	210	0.749074	0.003567
Total	287	2.801109	

C. Variate: Seedling height

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	178.09	59.36	2.87	
Rep.Cultivar stratum					
Cultivar	5	35874.62	7174.92	346.81	<.001
Residual	15	310.32	20.69	1.52	
Rep.Cultivar.*Units* stratum					
New_treatmets	1	3055.53	3055.53	225.04	<.001
Cultivar.New_treatmets	5	472.25	94.45	6.96	<.001
New_treatmets.RH	2	84.65	42.33	3.12	0.046
New_treatmets.Temp	2	160.46	80.23	5.91	0.023
Cultivar.New_treatmets.RH	10	151.54	15.15	1.12	0.010
Cultivar.New_treatmets.Temp	10	606.20	60.62	4.46	0.101
New_treatmets.RH.Temp	4	63.85	15.96	1.18	0.323
Cultivar.New_treatmets.RH.Temp	20	224.68	11.23	0.83	0.679
Residual	210	2851.37	13.58		
Total	287	44033.58			

D. Variate: Seedling leaf number

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	6.8333	2.2778	3.90	
Rep.Cultivar stratum					
Cultivar	5	34.3611	6.8722	11.78	<.001
Residual	15	8.7500	0.5833	1.66	
Rep.Cultivar.*Units* stratum					
New_treatmets	1	8.9630	8.9630	25.58	<.001
Cultivar.New_treatmets	5	24.2870	4.8574	13.86	<.001
New_treatmets.RH	2	0.3981	0.1991	0.57	0.567
New_treatmets.Temp	2	1.0370	0.5185	1.48	0.230
Cultivar.New_treatmets.RH	10	2.2685	0.2269	0.65	0.002
Cultivar.New_treatmets.Temp	10	3.6296	0.3630	1.04	0.414
New_treatmets.RH.Temp	4	0.7963	0.1991	0.57	0.686
Cultivar.New_treatmets.RH.Temp	20	5.7037	0.2852	0.81	0.695
Residual	210	73.5833	0.3504		
Total	287	170.6111			

E. Variate: Seedling shoot dry mass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	0.019879	0.009939	0.52	
Rep.Cultivar stratum					
Cultivar	5	0.648572	0.129714	6.81	0.005
Residual	10	0.190534	0.019053	1.93	
Rep.Cultivar.*Units* stratum					
New_treat	1	0.091271	0.091271	9.26	0.003
Cultivar.New_treat	5	0.139997	0.027999	2.84	0.016
New_treat.Temperatures	2	0.001608	0.000804	0.08	0.922
New_treat.Treatment	2	0.100221	0.050111	5.09	0.007
Cultivar.New_treat.Temperatures	10	0.068108	0.006811	0.69	0.732
Cultivar.New_treat.Treatment	10	0.300876	0.030088	3.05	0.001
New_treat.Temperatures.Treatment	4	0.052033	0.013008	1.32	0.263
Cultivar.New_treat.Temperatures.Treatment	20	0.095344	0.004767	0.48	0.971
Residual	252	2.482560	0.009851		
Total	323	4.191003			

F. Variate: Plant height

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	178.09	59.36	2.87	
Rep.Cultivar stratum					
Cultivar	5	35874.62	7174.92	346.81	<.001
Residual	15	310.32	20.69	1.52	
Rep.Cultivar.*Units* stratum					
New_treatmets	1	3055.53	3055.53	225.04	<.001
Cultivar.New_treatmets	5	472.25	94.45	6.96	<.001
New_treatmets.RH	2	84.65	42.33	3.12	0.046
New_treatmets.Temp	2	160.46	80.23	5.91	0.063
Cultivar.New_treatmets.RH	10	151.54	15.15	1.12	0.035
Cultivar.New_treatmets.Temp	10	606.20	60.62	4.46	0.101
New_treatmets.RH.Temp	4	63.85	15.96	1.18	0.323
Cultivar.New_treatmets.RH.Temp	20	224.68	11.23	0.83	0.679
Residual	210	2851.37	13.58		
Total	287	44033.58			

G. Variate: Plant leaf number

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	6.8333	2.2778	3.90	
Rep.Cultivar stratum					
Cultivar	5	34.3611	6.8722	11.78	<.001
Residual	15	8.7500	0.5833	1.66	
Rep.Cultivar.*Units* stratum					
New_treatmets	1	8.9630	8.9630	25.58	<.001
Cultivar.New_treatmets	5	24.2870	4.8574	13.86	<.001
New_treatmets.RH	2	0.3981	0.1991	0.57	0.050
New_treatmets.Temp	2	1.0370	0.5185	1.48	0.230
Cultivar.New_treatmets.RH	10	2.2685	0.2269	0.65	0.772
Cultivar.New_treatmets.Temp	10	3.6296	0.3630	1.04	0.414
New_treatmets.RH.Temp	4	0.7963	0.1991	0.57	0.686
Cultivar.New_treatmets.RH.Temp	20	5.7037	0.2852	0.81	0.695
Residual	210	73.5833	0.3504		
Total	287	170.6111			

H. Variate: Fruit number

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	2.76	1.38	0.19	
Rep.Cultivar stratum					
Cultivar	4	9597.72	2399.43	325.63	<.001
Residual	8	58.95	7.37	0.19	
Rep.Cultivar.*Units* stratum					
New_treat	1	1.20	1.20	0.03	0.859
Cultivar.New_treat	4	258.21	64.55	1.70	0.152
New_treat.Temperatures	2	12.40	6.20	0.16	0.850
New_treat.RH	2	1082.84	541.42	14.24	<.001
Cultivar.Newtreat.Temp	8	143.67	17.96	0.47	0.875
Cultivar.Newtreat.RH	8	1842.12	230.26	6.06	<.001
New_treat.Temp.RH	4	68.89	17.22	0.45	0.770
Cult.Newtreat.Temp.TRH	16	409.93	25.62	0.67	0.818
Residual	210	7983.19	38.02		

Total	269	21461.87			

I. Variate: Fruit mass

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	2331.	1165.	0.26	
Rep.Cultivar stratum					
Cultivar	4	1354584.	338646.	76.38	<.001
Residual	8	35471.	4434.	0.10	
Rep.Cultivar.*Units* stratum					
New_treat	1	176532.	176532.	4.15	0.043
Cultivar.New_treat	4	129189.	32297.	0.76	0.553
New_treat.Temperatures	2	7814.	3907.	0.09	0.912
New_treat.RH	2	2044306.	1022153.	24.04	<.001
Cultivar.New_treat.Temperatures	8	101037.	12630.	0.30	0.966
Cultivar.New_treat.RH	8	2069711.	258714.	6.09	<.001
New_treat.Temperatures.RH	4	27314.	6829.	0.16	0.958
Cultivar.New_treat.Temperatures.RH	16	409696.	25606.	0.60	0.880
Residual	210	8928272.	42516.		
Total	269	15286258.			

APPENDIX 4 Principal component analysis for pepper cultivars ('Santarini' and 'California Wonder'), Chilli and tomato cultivars ('Heinz', 'Marondera' and 'Roma') subjected to seed imbibition (10°C, 20°C, and 30°C) and dehydration (12% RH, 49% RH and 75% RH) treatments.

Santarini control

```
*****  Principal components analysis  *****

***  Latent Roots  ***

             1           2           3
         41.48        0.00        0.00

***  Percentage variation  ***

             1           2           3
        100.00        0.00        0.00

***  Trace  ***

       41.48

***  Latent Vectors (Loadings)  ***

                    1           2           3
          G%    -0.99999     0.00402     0.00087
          GI    -0.00404    -0.99934    -0.03620
   dry_mass_g   -0.00072     0.03621    -0.99934

***  Principal Component Scores  ***

                    1           2           3
           1     -3.750       0.043      -0.002
           2     -3.750      -0.058       0.006
           3     11.250       0.004      -0.002
           4     -3.750       0.028       0.011
           5     -3.750      -0.054       0.012
           6     11.250      -0.001      -0.001
           7     -3.750       0.040       0.000
           8      1.250      -0.035      -0.012
           9      6.250       0.052       0.008
          10     -8.750       0.031      -0.007
          11      1.250      -0.046      -0.004
          12     -3.750      -0.003      -0.009
```

Chilli control

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
65.72	0.00	0.00

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

65.73

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00619	0.00032
GI	-0.00618	-0.99957	0.02852
dry_mass_g	-0.00050	-0.02852	-0.99959

*** Principal Component Scores ***

	1	2	3
1	0.417	-0.006	-0.005
2	-4.584	-0.028	0.003
3	5.417	-0.037	0.000
4	0.418	0.173	-0.001
5	15.417	-0.031	-0.011
6	-4.584	-0.021	0.012
7	-9.583	0.056	-0.005
8	0.417	0.005	-0.003
9	10.417	0.012	0.015
10	-14.584	-0.056	-0.002
11	0.417	0.001	0.001
12	0.416	-0.070	-0.003

California Wonder control

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
21.970	0.003	0.000

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

21.97

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00575	0.00029
GI	-0.00575	-0.99998	0.00112
dry_mass_g	-0.00029	-0.00112	-1.00000

*** Principal Component Scores ***

	1	2	3
1	10.834	0.060	0.006
2	-4.167	-0.015	0.008
3	-4.167	-0.040	0.005
4	0.833	0.020	-0.004
5	0.833	-0.008	0.000
6	-4.167	-0.040	0.002
7	0.833	0.020	-0.010
8	5.833	-0.051	0.004
9	0.833	-0.105	-0.002
10	-4.166	0.074	-0.005
11	0.833	-0.005	-0.010
12	-4.166	0.089	0.006

Marondera control

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
119.71	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

119.7

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99995	0.01007	0.00061
GI	-0.01009	-0.99659	-0.08194
dry_mass_g	0.00022	0.08194	-0.99664

*** Principal Component Scores ***

	1	2	3
1	11.667	-0.023	0.004
2	-8.334	-0.010	0.001
3	11.667	-0.026	0.001
4	16.668	0.020	0.002
5	-8.334	-0.010	0.005
6	6.667	0.044	0.001
7	6.667	-0.024	-0.012
8	-8.334	-0.010	0.005
9	-13.334	0.005	-0.006
10	6.667	0.021	-0.002
11	-8.334	-0.010	0.003
12	-13.334	0.023	-0.003

Roma control

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
6.063	0.006	0.000

*** Percentage variation ***

1	2	3
99.91	0.09	0.00

*** Trace ***

6.069

*** Latent Vectors (Loadings) ***

	1	2	3
G%	0.99981	-0.01973	-0.00073
GI	0.01974	0.99967	0.01657
dry_mass_g	-0.00040	0.01658	-0.99986

*** Principal Component Scores ***

	1	2	3
1	3.3342	0.0089	0.0021
2	3.3338	-0.0091	-0.0001
3	-1.6692	-0.1143	-0.0009
4	3.3338	-0.0090	-0.0031
5	-1.6656	0.0687	-0.0039
6	-1.6692	-0.1144	0.0011
7	-1.6656	0.0686	0.0051
8	-1.6656	0.0687	-0.0029
9	-1.6692	-0.1143	0.0001
10	-1.6656	0.0686	0.0061
11	-1.6656	0.0687	-0.0049
12	3.3342	0.0089	0.0011

Heinz control

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
6.818	0.000	0.000

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

6.818

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-1.00000	0.00196	-0.00038
GI	-0.00200	-0.97856	0.20595
dry_mass_g	-0.00003	-0.20595	-0.97856

*** Principal Component Scores ***

	1	2	3
1	2.5000	0.0006	0.0029
2	2.5000	0.0004	0.0020
3	-2.5000	0.0100	-0.0009
4	2.5000	0.0006	0.0029
5	2.5000	-0.0010	-0.0049
6	-2.5000	0.0104	0.0010
7	2.5000	-0.0004	-0.0020
8	-2.5001	-0.0292	0.0022
9	-2.5000	0.0102	0.0001
10	2.5000	-0.0002	-0.0010
11	-2.5000	-0.0120	-0.0034
12	-2.5000	0.0104	0.0010

Santarini 10°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
77.84	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

77.85

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00679	-0.00089
GI	-0.00685	-0.99032	0.13864
dry_mass_g	-0.00006	-0.13864	-0.99034

*** Principal Component Scores ***

	1	2	3
1	3.750	0.017	-0.003
2	3.750	-0.054	0.008
3	8.750	-0.014	-0.001
4	3.750	0.020	0.016
5	3.750	0.016	-0.010
6	-11.250	0.007	-0.014
7	3.750	0.036	0.001
8	8.750	-0.008	-0.002
9	-6.250	0.015	0.009
10	-16.250	0.006	0.007
11	8.750	-0.007	-0.006
12	-11.250	-0.035	-0.004

Chilli 10°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
78.79	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

78.79

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99997	0.00709	0.00066
GI	-0.00710	-0.99973	-0.02218
dry_mass_g	-0.00050	0.02218	-0.99975

*** Principal Component Scores ***

	1	2	3
1	-3.333	0.006	-0.002
2	1.667	-0.022	0.000
3	1.667	0.014	-0.005
4	21.667	0.011	-0.002
5	-13.334	-0.020	-0.007
6	1.667	0.006	0.009
7	6.667	-0.015	-0.002
8	-8.334	-0.016	0.009
9	1.667	-0.022	0.003
10	-3.333	0.056	0.002
11	-8.333	0.028	-0.002
12	1.667	-0.026	-0.003

California Wonder 10°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
52.08	0.00	0.00

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

52.09

*** Latent Vectors (Loadings) ***

	1	2	3
G%	1.00000	-0.00007	-0.00033
GI	0.00008	0.99916	0.04098
dry_mass_g	-0.00032	0.04098	-0.99916

*** Principal Component Scores ***

	1	2	3
1	5.417	0.042	0.007
2	0.417	0.028	0.005
3	5.417	0.042	0.005
4	15.417	-0.113	-0.003
5	0.417	0.025	0.000
6	-4.583	0.018	-0.003
7	-4.583	-0.111	0.002
8	0.417	0.046	0.009
9	-4.583	0.104	-0.007
10	-14.583	-0.089	0.004
11	0.417	-0.003	-0.017
12	0.417	0.010	0.000

Marondera 10°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
109.09	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

109.1

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00561	0.00043
GI	-0.00561	-0.99998	-0.00250
dry_mass_g	-0.00041	0.00250	-1.00000

*** Principal Component Scores ***

	1	2	3
1	15.000	-0.028	-0.024
2	-10.001	-0.091	0.003
3	5.000	0.007	0.008
4	0.000	0.071	-0.004
5	-10.000	-0.005	-0.006
6	10.000	0.000	0.006
7	-15.000	0.045	-0.005
8	-10.000	-0.005	0.000
9	10.000	0.000	0.006
10	10.000	-0.018	0.006
11	-10.000	-0.005	0.003
12	5.000	0.029	0.007

Roma 10°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
74.82	0.00	0.00

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

74.82

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99996	0.00901	0.00016
GI	-0.00901	-0.99918	-0.03938
dry_mass_g	0.00020	0.03938	-0.99922

*** Principal Component Scores ***

	1	2	3
1	7.084	0.022	0.003
2	-7.917	-0.032	-0.012
3	-2.917	-0.056	0.002
4	7.084	0.014	0.006
5	-2.916	0.127	0.001
6	-7.917	-0.050	0.003
7	17.084	-0.043	-0.001
8	-2.916	0.127	-0.002
9	-7.917	-0.032	0.003
10	12.084	-0.008	-0.007
11	-7.917	-0.011	0.000
12	-2.917	-0.056	0.003

Heinz 10°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
97.55	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

97.55

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99996	0.00918	-0.00117
GI	-0.00925	-0.99311	0.11686
dry_mass_g	0.00009	-0.11686	-0.99315

*** Principal Component Scores ***

	1	2	3
1	-15.418	-0.026	-0.003
2	4.584	0.010	-0.009
3	-0.416	0.043	0.001
4	-15.417	-0.008	-0.003
5	9.583	-0.035	0.003
6	-0.416	0.036	0.004
7	4.584	0.011	-0.001
8	9.583	-0.035	0.000
9	4.584	0.012	0.006
10	9.584	-0.014	0.003
11	4.584	0.011	-0.008
12	-15.417	-0.007	0.007

Santarini 20°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
47.54	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

47.54

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00617	0.00042
GI	-0.00616	-0.98887	-0.14867
dry_mass_g	0.00050	0.14867	-0.98889

*** Principal Component Scores ***

	1	2	3
1	-2.083	0.024	-0.001
2	12.917	0.008	0.004
3	-7.084	-0.030	0.033
4	7.917	-0.012	-0.011
5	2.917	-0.017	0.011
6	-7.084	-0.046	-0.028
7	2.917	-0.031	-0.009
8	7.917	0.000	0.006
9	-7.083	0.041	-0.012
10	-2.083	0.077	0.001
11	-2.083	-0.001	-0.004
12	-7.084	-0.012	0.010

Chilli 20°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
29.356	0.002	0.000

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

29.36

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99999	0.00327	-0.00001
GI	-0.00326	-0.99469	0.10288
dry_mass_g	-0.00033	-0.10288	-0.99469

*** Principal Component Scores ***

	1	2	3
1	-4.583	0.111	0.002
2	5.417	-0.001	-0.003
3	0.417	-0.006	-0.004
4	0.417	-0.020	-0.001
5	-4.583	-0.014	0.009
6	5.417	0.016	-0.007
7	10.417	-0.006	0.005
8	0.417	-0.045	0.004
9	-4.583	-0.018	0.004
10	0.417	0.001	-0.002
11	0.417	0.019	0.000
12	-9.584	-0.038	-0.007

California Wonder 20°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
83.91	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

83.91

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99997	0.00746	0.00021
GI	-0.00746	-0.99844	-0.05535
dry_mass_g	0.00020	0.05535	-0.99847

*** Principal Component Scores ***

	1	2	3
1	4.584	0.080	-0.010
2	-5.416	0.050	0.003
3	9.583	-0.087	-0.002
4	14.584	0.062	0.002
5	4.583	-0.025	0.003
6	-0.417	-0.097	-0.004
7	-0.416	0.044	0.003
8	4.583	0.000	0.004
9	-15.417	0.014	0.001
10	-5.417	0.032	0.000
11	4.583	-0.039	0.002
12	-15.417	-0.033	-0.002

Marondera 20°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
144.71	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

144.7

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99996	0.00922	-0.00038
GI	-0.00923	-0.99952	0.02951
dry_mass_g	0.00011	-0.02951	-0.99956

*** Principal Component Scores ***

	1	2	3
1	-0.833	0.000	-0.003
2	9.167	0.030	-0.003
3	-10.834	-0.008	-0.001
4	14.167	-0.020	-0.001
5	14.167	0.002	-0.004
6	-10.834	0.010	0.004
7	14.167	-0.006	0.003
8	-10.834	-0.022	-0.005
9	-10.834	-0.007	0.006
10	14.167	0.001	0.005
11	-10.834	0.010	-0.009
12	-10.834	0.011	0.007

Roma 20°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
90.91	0.01	0.00

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

90.92

*** Latent Vectors (Loadings) ***

	1	2	3
G%	0.99998	-0.00663	0.00049
GI	0.00665	0.99921	-0.03927
dry_mass_g	0.00023	-0.03927	-0.99923

*** Principal Component Scores ***

	1	2	3
1	-15.000	0.035	-0.001
2	10.001	0.052	-0.002
3	5.001	0.085	0.000
4	-15.000	0.035	-0.001
5	4.999	-0.098	0.000
6	10.001	0.091	-0.003
7	-10.000	0.001	-0.002
8	4.999	-0.120	-0.006
9	10.001	0.073	0.004
10	-5.000	-0.017	0.004
11	4.999	-0.119	0.005
12	-5.000	-0.017	0.002

Heinz 20°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
132.40	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

132.4

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99996	0.00862	0.00048
GI	-0.00863	-0.99924	-0.03810
dry_mass_g	-0.00015	0.03810	-0.99927

*** Principal Component Scores ***

	1	2	3
1	13.750	-0.012	-0.001
2	-11.250	0.000	0.002
3	13.750	-0.012	0.001
4	13.750	-0.033	0.002
5	-6.249	0.140	0.003
6	-11.251	-0.039	0.001
7	3.750	0.038	-0.005
8	-11.251	-0.039	-0.010
9	-11.251	-0.040	0.007
10	3.750	0.031	-0.005
11	-11.251	-0.021	0.002
12	13.750	-0.012	0.002

Santarini 30°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
55.12	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

55.12

*** Latent Vectors (Loadings) ***

	1	2	3
G%	0.99998	-0.00555	-0.00128
GI	0.00570	0.97665	0.21478
dry_mass_g	-0.00006	0.21478	-0.97666

*** Principal Component Scores ***

	1	2	3
1	1.250	-0.050	-0.001
2	1.250	0.008	-0.002
3	-3.750	-0.011	-0.013
4	1.250	0.035	0.007
5	1.250	0.013	-0.012
6	6.250	-0.001	0.002
7	-3.750	-0.014	0.013
8	1.250	0.025	0.004
9	6.250	-0.011	0.004
10	-3.750	-0.022	0.002
11	-18.750	0.015	-0.002
12	11.250	0.013	-0.005

Chilli 30°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
64.21	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

64.21

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00688	0.00101
GI	-0.00694	-0.99695	-0.07769
dry_mass_g	-0.00047	0.07769	-0.99698

*** Principal Component Scores ***

	1	2	3
1	-1.250	-0.002	-0.008
2	8.750	0.010	0.003
3	-6.250	-0.026	0.009
4	-1.250	-0.016	-0.005
5	8.750	0.022	-0.007
6	13.750	0.004	0.006
7	-6.250	-0.011	0.003
8	-1.250	-0.005	-0.003
9	3.750	-0.019	-0.004
10	-1.250	0.026	0.008
11	-16.250	0.031	-0.001
12	-1.250	-0.013	-0.001

California wonder 30°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
40.91	0.00	0.00

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

40.92

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99995	0.01002	0.00073
GI	-0.01004	-0.99922	-0.03807
dry_mass_g	-0.00034	0.03808	-0.99927

*** Principal Component Scores ***

	1	2	3
1	5.000	0.020	0.003
2	0.000	0.038	0.004
3	5.000	0.013	0.000
4	0.001	0.106	-0.008
5	10.000	-0.041	0.000
6	-5.001	-0.033	-0.002
7	5.000	-0.059	-0.002
8	0.000	0.005	0.005
9	-10.000	0.053	0.004
10	-10.001	-0.065	0.003
11	5.000	0.005	0.003
12	-5.001	-0.044	-0.009

Marondera 30°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
52.09	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

52.09

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00693	-0.00029
GI	-0.00694	-0.99947	0.03181
dry_mass_g	0.00007	-0.03182	-0.99949

*** Principal Component Scores ***

	1	2	3
1	-2.083	-0.011	-0.012
2	2.917	-0.002	0.003
3	-2.083	0.033	0.007
4	-2.083	0.011	0.000
5	7.917	-0.016	0.000
6	-2.083	0.054	-0.002
7	-17.084	-0.042	0.001
8	7.917	-0.016	-0.001
9	2.917	0.019	0.004
10	-7.083	0.007	0.007
11	2.917	-0.002	-0.016
12	7.917	-0.036	0.011

Roma 30°C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
46.03	0.00	0.00

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

46.03

*** Latent Vectors (Loadings) ***

	1	2	3
G%	0.99994	-0.01118	0.00100
GI	0.01122	0.99786	-0.06438
dry_mass_g	0.00028	-0.06439	-0.99792

*** Principal Component Scores ***

	1	2	3
1	-8.750	0.025	0.000
2	1.249	-0.110	-0.009
3	-8.750	0.026	0.005
4	6.251	0.057	0.005
5	6.251	0.018	-0.003
6	-8.750	0.018	-0.004
7	6.251	0.039	-0.004
8	6.251	0.018	-0.002
9	-8.750	0.025	-0.003
10	6.251	0.057	0.001
11	1.249	-0.065	0.008
12	1.249	-0.109	0.006

Heinz 30 °C

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
124.82	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

124.8

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99995	0.00955	-0.00006
GI	-0.00955	-0.99984	0.01542
dry_mass_g	-0.00009	-0.01542	-0.99988

*** Principal Component Scores ***

	1	2	3
1	9.584	0.011	-0.001
2	-10.417	-0.020	-0.016
3	-10.417	0.019	0.010
4	-10.417	-0.020	0.008
5	-10.417	0.019	-0.003
6	4.584	0.044	-0.002
7	14.584	-0.016	0.001
8	9.584	0.011	-0.004
9	-10.417	-0.020	0.002
10	9.584	0.011	0.001
11	14.584	-0.037	0.003
12	-10.417	-0.002	-0.001

Santarini 12% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
59.66	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

59.66

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99997	0.00712	0.00005
GI	-0.00710	-0.99674	0.08031
dry_mass_g	-0.00062	-0.08031	-0.99677

*** Principal Component Scores ***

	1	2	3
1	11.250	0.007	-0.006
2	-8.750	0.010	0.002
3	-3.750	0.035	0.000
4	11.250	0.008	0.012
5	1.250	-0.037	-0.011
6	-3.750	-0.051	-0.004
7	11.250	0.025	-0.001
8	-3.750	-0.050	0.000
9	1.250	-0.010	0.006
10	-8.750	0.000	0.014
11	-8.750	0.063	-0.009
12	1.250	-0.001	-0.004

Chilli 12% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
55.12	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

55.12

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99999	0.00506	-0.00003
GI	-0.00505	-0.99696	0.07774
dry_mass_g	-0.00036	-0.07774	-0.99697

*** Principal Component Scores ***

	1	2	3
1	-6.250	-0.015	0.000
2	-6.249	0.117	0.001
3	-1.250	-0.027	-0.006
4	-1.250	-0.023	-0.005
5	-1.250	-0.041	-0.001
6	18.750	0.041	0.000
7	3.750	-0.016	0.003
8	8.750	-0.027	0.003
9	-6.250	-0.044	0.006
10	-6.250	0.035	-0.001
11	-1.250	-0.002	-0.006
12	-1.250	0.003	0.006

California wonder 12% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
93.00	0.01	0.00

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

93.00

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00644	-0.00011
GI	-0.00644	-0.99993	-0.01013
dry_mass_g	0.00017	0.01013	-0.99995

*** Principal Component Scores ***

	1	2	3
1	-4.584	-0.024	0.004
2	5.417	0.030	-0.013
3	0.417	-0.020	0.005
4	-14.582	0.195	0.005
5	15.417	0.022	0.000
6	-4.583	0.047	-0.012
7	5.417	0.066	0.005
8	0.417	-0.010	0.002
9	0.416	-0.099	0.001
10	15.417	-0.021	0.004
11	-4.584	-0.028	0.000
12	-14.585	-0.159	-0.001

Marondera 12% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
100.57	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

100.6

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99999	0.00527	0.00007
GI	-0.00527	-0.99986	-0.01584
dry_mass_g	0.00002	0.01584	-0.99987

*** Principal Component Scores ***

	1	2	3
1	13.750	-0.016	-0.014
2	-6.250	-0.054	-0.003
3	-1.250	-0.001	-0.009
4	-1.250	0.077	0.000
5	8.750	-0.015	-0.002
6	-1.250	0.020	0.004
7	-16.250	0.046	-0.008
8	8.750	-0.001	0.002
9	-16.251	-0.058	0.003
10	8.750	-0.008	0.014
11	8.750	0.006	0.004
12	-6.250	0.007	0.011

Roma12% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
93.00	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

93.00

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99996	0.00931	0.00004
GI	-0.00931	-0.99993	0.00718
dry_mass_g	-0.00011	-0.00718	-0.99997

*** Principal Component Scores ***

	1	2	3
1	0.417	0.040	0.000
2	10.417	-0.038	0.003
3	0.417	0.033	0.000
4	0.417	0.033	0.004
5	10.417	-0.038	0.003
6	-14.584	-0.027	0.005
7	10.417	-0.027	-0.003
8	5.417	0.009	0.000
9	-14.584	-0.009	-0.007
10	5.417	0.009	-0.010
11	0.417	0.040	0.004
12	-14.584	-0.027	0.001

Heinz 12% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
79.36	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

79.36

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99996	0.00937	0.00071
GI	-0.00940	-0.99762	-0.06831
dry_mass_g	-0.00007	0.06832	-0.99766

*** Principal Component Scores ***

	1	2	3
1	-17.084	-0.024	-0.005
2	7.917	-0.017	0.000
3	2.917	0.009	-0.002
4	-2.083	0.034	0.008
5	7.917	-0.038	0.003
6	-17.084	-0.025	0.004
7	2.917	0.009	0.001
8	-2.083	0.042	-0.003
9	7.917	-0.017	-0.002
10	7.917	-0.017	-0.001
11	-2.083	0.035	-0.003
12	2.917	0.009	0.000

Santarini 49 % RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
87.88	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

87.88

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00686	-0.00006
GI	-0.00686	-0.99987	0.01467
dry_mass_g	-0.00004	-0.01467	-0.99989

*** Principal Component Scores ***

	1	2	3
1	6.667	-0.036	0.008
2	1.667	0.009	0.001
3	-8.334	0.003	-0.007
4	6.667	0.036	-0.001
5	-8.334	-0.008	0.018
6	-8.334	0.000	-0.018
7	11.667	0.011	0.004
8	-3.333	0.005	0.008
9	-8.334	-0.015	-0.005
10	11.667	0.013	0.000
11	-13.334	0.009	0.003
12	11.667	-0.027	-0.011

Chilli 49% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
75.00	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

75.00

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00671	0.00049
GI	-0.00672	-0.99967	-0.02483
dry_mass_g	-0.00032	0.02484	-0.99969

*** Principal Component Scores ***

	1	2	3
1	2.500	-0.019	0.004
2	7.500	-0.006	-0.005
3	12.500	0.003	0.005
4	-12.500	-0.022	-0.006
5	-2.500	0.015	0.006
6	12.500	0.014	-0.005
7	-7.500	-0.016	0.010
8	2.500	-0.033	-0.003
9	2.500	-0.015	-0.002
10	-7.500	0.028	0.000
11	2.500	0.031	0.000
12	-12.500	0.018	-0.004

California wonder 49% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
15.720	0.000	0.000

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

15.72

*** Latent Vectors (Loadings) ***

	1	2	3
G%	1.00000	-0.00206	0.00076
GI	0.00218	0.96717	-0.25413
dry_mass_g	0.00021	-0.25414	-0.96717

*** Principal Component Scores ***

	1	2	3
1	0.417	-0.001	0.001
2	5.417	-0.011	0.005
3	5.417	-0.002	0.003
4	0.417	-0.006	-0.003
5	-4.583	0.010	0.000
6	-4.583	-0.001	0.003
7	0.417	0.017	-0.001
8	-4.583	-0.014	0.006
9	5.417	0.031	-0.004
10	0.417	-0.037	-0.011
11	-4.583	0.023	-0.004
12	0.417	-0.007	0.005

Marondera 49% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
106.64	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

106.6

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99996	0.00867	0.00013
GI	-0.00867	-0.99994	-0.00720
dry_mass_g	-0.00007	0.00720	-0.99997

*** Principal Component Scores ***

	1	2	3
1	-7.917	-0.043	0.005
2	7.084	0.010	0.000
3	7.084	0.010	0.008
4	-7.917	0.043	-0.004
5	12.084	-0.015	-0.004
6	12.084	-0.013	0.003
7	-7.917	0.043	0.002
8	-12.918	-0.053	-0.001
9	12.084	-0.013	0.002
10	-7.917	0.043	0.005
11	-12.917	-0.021	-0.004
12	7.084	0.010	-0.011

Roma 49% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
6.638	0.000	0.000

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

6.638

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99930	0.03735	0.00163
GI	-0.03739	-0.99777	-0.05522
dry_mass_g	0.00044	0.05524	-0.99847

*** Principal Component Scores ***

	1	2	3
1	-2.9193	-0.0165	-0.0051
2	-2.9186	0.0040	0.0030
3	2.0848	0.0009	-0.0140
4	2.0848	-0.0001	0.0040
5	2.0848	0.0000	0.0020
6	-2.9185	0.0044	-0.0030
7	2.0848	0.0001	0.0010
8	2.0856	0.0214	-0.0038
9	-2.9185	0.0043	-0.0020
10	-2.9186	0.0038	0.0070
11	2.0856	0.0208	0.0072
12	2.0832	-0.0431	0.0036

Heinz 49% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
118.19	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

118.2

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99997	0.00780	-0.00014
GI	-0.00780	-0.99950	0.03071
dry_mass_g	-0.00010	-0.03071	-0.99953

*** Principal Component Scores ***

	1	2	3
1	10.000	0.006	-0.003
2	-10.000	-0.020	0.007
3	-10.001	-0.060	-0.011
4	-4.999	0.124	0.001
5	-4.999	0.124	-0.001
6	-10.000	-0.020	0.001
7	15.000	-0.033	0.000
8	-10.001	-0.060	-0.002
9	10.000	0.006	-0.001
10	10.000	0.006	-0.002
11	-10.001	-0.041	0.008
12	15.000	-0.032	0.005

Santarini 75% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
84.10	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

84.10

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99997	0.00696	0.00154
GI	-0.00713	-0.97082	-0.23972
dry_mass_g	0.00017	0.23973	-0.97084

*** Principal Component Scores ***

	1	2	3
1	22.500	-0.013	0.002
2	-7.500	-0.029	0.036
3	7.500	0.008	-0.014
4	2.500	0.018	-0.005
5	-7.501	-0.039	-0.026
6	-2.500	0.007	-0.003
7	7.500	0.015	0.020
8	-7.500	0.047	-0.003
9	-2.500	0.016	0.003
10	2.500	-0.025	-0.011
11	-7.500	-0.009	0.015
12	-7.500	0.005	-0.015

Chilli 75% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
38.45	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

38.45

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99998	0.00632	0.00205
GI	-0.00660	-0.97940	-0.20183
dry_mass_g	-0.00073	0.20183	-0.97942

*** Principal Component Scores ***

	1	2	3
1	-0.417	0.023	0.002
2	-0.417	0.013	-0.005
3	-5.417	-0.033	0.007
4	-0.417	0.013	0.014
5	4.584	0.019	-0.007
6	14.584	0.005	0.003
7	-0.417	-0.015	0.003
8	-5.417	0.015	0.004
9	4.583	-0.020	-0.008
10	-0.417	-0.017	-0.003
11	-10.417	0.015	-0.007
12	-0.417	-0.017	-0.003

California wonder 75% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
76.52	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

76.52

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99999	0.00508	-0.00038
GI	-0.00509	-0.99946	0.03241
dry_mass_g	0.00022	-0.03241	-0.99947

*** Principal Component Scores ***

	1	2	3
1	-0.833	0.059	0.002
2	14.167	-0.029	0.008
3	4.167	0.062	0.002
4	9.167	0.032	-0.005
5	4.166	-0.063	0.007
6	-5.834	-0.034	-0.001
7	9.167	-0.054	-0.010
8	-10.833	0.013	0.003
9	-10.833	0.027	-0.003
10	4.167	0.065	-0.002
11	-10.834	-0.034	0.005
12	-5.834	-0.045	-0.008

Marondera 75% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
114.22	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

114.2

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99995	0.00991	0.00064
GI	-0.00993	-0.99935	-0.03475
dry_mass_g	-0.00029	0.03476	-0.99940

*** Principal Component Scores ***

	1	2	3
1	6.250	0.000	0.003
2	-13.751	-0.023	-0.005
3	1.251	0.050	0.004
4	11.250	-0.028	0.000
5	-13.751	-0.005	0.000
6	1.251	0.071	-0.004
7	11.250	-0.028	0.000
8	-13.751	-0.023	0.002
9	6.251	0.021	-0.003
10	6.251	0.021	0.002
11	-13.751	-0.005	0.003
12	11.250	-0.049	-0.002

Roma 75% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
42.43	0.00	0.00

*** Percentage variation ***

1	2	3
99.99	0.01	0.00

*** Trace ***

42.43

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99992	0.01281	0.00044
GI	-0.01281	-0.99840	-0.05513
dry_mass_g	0.00027	0.05513	-0.99848

*** Principal Component Scores ***

	1	2	3
1	-1.667	-0.039	0.000
2	-1.667	-0.039	-0.003
3	8.334	-0.006	0.005
4	-6.667	-0.014	0.002
5	-6.667	-0.013	-0.006
6	8.334	0.001	-0.005
7	-6.667	0.004	0.002
8	-6.667	0.004	0.001
9	8.334	-0.006	-0.003
10	-1.667	-0.039	0.001
11	8.334	0.001	0.003
12	-1.665	0.145	0.000

Heinz 75% RH

***** Principal components analysis *****

*** Latent Roots ***

1	2	3
102.10	0.00	0.00

*** Percentage variation ***

1	2	3
100.00	0.00	0.00

*** Trace ***

102.1

*** Latent Vectors (Loadings) ***

	1	2	3
G%	-0.99994	0.01081	0.00019
GI	-0.01081	-0.99986	-0.01240
dry_mass_g	-0.00005	0.01240	-0.99992

*** Principal Component Scores ***

	1	2	3
1	7.084	0.035	0.003
2	17.084	-0.037	-0.002
3	-7.917	0.030	0.003
4	-7.917	-0.009	0.005
5	-7.917	-0.009	-0.003
6	7.084	0.036	-0.007
7	12.084	-0.004	0.003
8	-7.917	-0.009	0.003
9	-7.917	-0.009	-0.005
10	12.084	-0.004	0.003
11	-7.917	-0.009	0.003
12	-7.917	-0.009	-0.005