UNIVERSITI PUTRA MALAYSIA

AGRONOMIC AND BIOCHEMICAL EXPRESSION OF ZINC, MANGANESE, AND PHOSPHORUS INTERACTION IN SWEET CORN PLANTS (ZEA MAYS L. VAR. SACCHARATA (STURTEV.) L. H. BAILEY)

AMIN SOLTANGHEISI

FP 2015 62

© COPYRIGHT UPM

AGRONOMIC AND BIOCHEMICAL EXPRESSION OF ZINC, MANGANESE, AND PHOSPHORUS INTERACTION IN SWEET CORN PLANTS (*ZEA MAYS* L. VAR. SACCHARATA (STURTEV.) L. H. BAILEY)

By

AMIN SOLTANGHEISI

Thesis Submitted to the School of Graduate Studies,
Universiti Putra Malaysia, in Fulfilment of the
Requirement for the Degree of
Doctor of Philosophy

February 2015

COPYRIGHT

All material contained within the thesis, including without limitation text, logos, icons, photographs and all other artwork, is copyright material of Universiti Putra Malaysia unless otherwise stated. Use may be made of any material contained within the thesis for non-commercial purposes from the copyright holder. Commercial use of material may only be made with the express, prior, written permission of Universiti Putra Malaysia.

Copyright © Universiti Putra Malaysia

© COPYRIGHT UPM

DEDICATION

I would like to dedicate this thesis to my beloved wife

Jasmine

for nursing me with affections and love

© COPYRIGHT UPM

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

AGRONOMIC AND BIOCHEMICAL EXPRESSION OF ZINC, MANGANESE, AND PHOSPHORUS INTERACTIONS IN SWEET CORN PLANTS (*ZEA MAYS* L. VAR. SACCHARATA (STURTEV.) L. H. BAILEY)

By

AMIN SOLTANGHEISI

February 2015

Chairman: Professor Zaharah Abdul Rahman, PhD

Faculty: Agriculture

Zinc and phosphorus have antagonistic effects on the absorption and translocation of each other in plants. Phosphorus-induced Zn deficiency is more common than Zn-induced P deficiency because growers commonly apply large amounts of P fertilizer as compared to Zn fertilizer. Manganese and Zn also interact with each other and this interaction can affect the yield of corn plants. This research was conducted to examine the effects of different levels of Zn, Mn, and P on the yield, Zn, Mn, and P concentrations and uptake, the ultrastructure of chloroplast, physiological characteristics, root growth parameters, and chlorophyll contents of sweet corn plants. Sweet corn was grown in nutrient culture containing all combinations of Zn as $ZnSO_4.7H_2O$ at levels of 0.0, 5.0, 10.0, and 20.0 mg L^{-1} and of P as KH_2PO_4 at levels of 0.0, 20.0, 40.0, and 80.0 mg L^{-1}. The treatment Zn_0P_{20} produced the highest yield and the yields decreased with P application in combination with Zn. The lowest dry weight of young corn plants was recorded under Zn_0P_{80} treatment at both harvesting times due to both Zn deficiency and P toxicity. Chlorophyll content decreased with high Zn and P applications and this can be attributed to the interactions of Zn and P with iron in the growth medium. The study has shown that Zn deficiency can enhance P uptake and translocation to such an extent that P may accumulate to toxic level in leaves. Sweet corn was grown in nutrient culture containing all combinations of P at levels of 0.0 and 80.0 mg L^{-1} as KH_2PO_4 and Zn at levels of 0.0 and 20.0 mg L^{-1} as $ZnSO_4.7H_2O$, and harvested at 14 and 28 days after transplanting. Phosphorus and Zn concentrations in leaves increased with increasing P and Zn concentration in nutrient solution. Zinc supply did not affect P concentration but Zn concentration reduced with increasing P supply in nutrient solution at both harvests. Carbonic anhydrase activity in leaves was enhanced with increasing Zn levels and decreased with increasing P levels at both harvest times. Carbonic anhydrase activity is a

© COPYRIGHT UPM

better indicator of Zn nutritional status than Zn concentration alone. The ultrastructure of chloroplast was affected by P and Zn supply. Sweet corn was grown in nutrient culture containing all combinations of Zn and Mn at levels of 0.0, 0.1, 1.0, and 10.0 mg L^{-1} as $ZnSO_4.7H_2O$ and $MnSO_4.H_2O$, respectively and harvested at 28 days after transplanting. Manganese and Zn concentrations in roots and shoots increased with increasing Mn and Zn concentration in nutrient solution. Zinc concentration in both roots and shoots was enhanced with increasing Mn levels. Manganese concentration in shoots did not show any correlation with Zn concentration in nutrient solution but Mn concentration in roots decreased with increasing levels of Zn. The lowest dry weight of young corn plants was recorded under $Zn_{10}Mn_0$ treatment due to Mn deficiency. Sweet corn grown in pot culture containing all combinations of Zn at levels of 0.0, 5.0, and 10.0 mg kg^{-1} soil and P at levels of 0.0, 50.0, 100.0, and 200.0 mg kg^{-1} soil as $ZnSO_4.7H_2O$ and KH_2PO_4, respectively and harvested at 28 days after transplanting showed dry matter yield increased with P supply, while Zn application did not show any significant effect on this parameter. Zinc and P uptake by shoots increased with increasing Zn and P application to the soil. Zn concentration in shoots decreased with increasing P supply, but P concentration and uptake was enhanced. Phosphorus-induced Zn deficiency in this study is mostly related to the dilution effect. The percentage of P derived from fertilizer reduced with increasing Zn application, although P uptake by shoots was unchanged.

© COPYRIGHT UPM

Abstrak tesis yang dikemukakan kedapa Senati Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

EKSPRESI AGRONOMIK DAN BIOKIMIA TERHADAP INTERAKSI ZINK, MANGAN, DAN FOSFORUS DALAM TANAMAN JAGUNG MANIS (*ZEA MAYS* L. VAR. SACCHARATA (STURTEV.) L. H. BAILEY)

Oleh

AMIN SOLTANGHEISI

Februari 2015

Pengerusi: Professor Zaharah Abdul Rahman, PhD

Fakulti: Pertanian

Zink dan fosforus mempunyai kesan bermusuhan ke atas penyerapan dan translokasi satu sama lain dalam tumbuhan. Kekurangan Zn disebabkan oleh berlebihan P adalah lebih biasa berlaku daripada kekurangan P yand disebabkan oleh berlebihan baja Zn. Ini adalah kerana penanam biasanya memberi jumlah baja P yang lebih tinggi berbanding dengan baja Zn. Mangan (Mn) dan zink (Zn) juga berinteraksi antara satu sama lain dan interaksi ini boleh memberi kesan pada hasil tanaman jagung. Kajian ini dijalankan untuk mengkaji kesan tahap berbeza unsur Zn, Mn, dan P pada hasil, kepekatan dan pengambilan Zn, Mn, dan P, ultrastruktur kloroplas, ciri-ciri fisiologi, parameter pertumbuhan akar, dan kandungan klorofil tanaman jagung manis. Jagung manis ditanam menggunakan larutan nutrien yang mengandungi semua kombinasi Zn diberi sebagai $ZnSO_4.7H_2O$ pada tahap 0.0, 5.0, 10.0, dan 20.0 mg L^{-1} dan P sebagai KH_2PO_4 pada tahap 0.0, 20.0, 40.0, dan 80.0 mg L^{-1}. Rawatan Zn_0P_{20} memberi hasil tertinggi dan hasil telah menurun dengan pemberian P ber kombinasi dengan Zn. Berat kering tanaman jagong muda yang paling rendah telah direkodkan di dalam rawatan Zn_0P_{80} pada kedua-dua penuaian disebabkan oleh kekurangan Zn dan ketoksikan P. Kandungan klorofil menurun dengan aplikasi Zn yang tinggi bersama P dan ini boleh dikaitkan dengan interaksi Zn dan P dengan Ferum dalam medium pertumbuhan. Kajian ini telah menunjukkan bahawa kekurangan Zn boleh meningkatkan pengambilan dan translokasi P, dimana P boleh terkumpul dalam daun ke tahap toksik. Jagung manis ditanam dalam larutan nutrien yang mengandungi semua kombinasi P pada tahap 0.0 dan 80.0 mg L^{-1} diberi sebagai KH_2PO_4 dan Zn pada tahap 0.0 dan 20.0 mg L^{-1} diberi sebagai $ZnSO_4.7H_2O$, dan dituai pada 14 dan 28 hari selepas pemindahan. Kepekatan P dan Zn dalam daun meningkat dengan peningkatan P dan Zn dalam larutan nutrien. Kepekatan Zn tidak mempengaruhi kandungan P tetapi kepekatan Zn berkurangan dengan

© COPYRIGHT UPM

meningkatnya bekalan P dalam larutan nutrien di kedua-dua tuaian. Aktiviti karbonik enhidrasa dalam daun telah dipertingkatkan dengan meningkatnya tahap Zn, dan menurun dengan peningkatan aras P di kedua-dua tuaian. Aktiviti karbonik enhidrasa adalah petunjuk yang lebih baik terhadap status pemakanan Zn daripada kepekatan Zn sahaja. Ultrastruktur kloroplas dipengaruhi oleh bekalan P dan Zn. Jagung manis ditanam dalam larutan nutrien yang mengandungi semua kombinasi Zn dan Mn pada tahap 0.0, 0.1, 1.0, dan 10.0 mg L^{-1} sebagai $ZnSO_4.7H_2O$ dan $MnSO_4.H_2O$, dan dituai 28 hari selepas pemindahan menunjukkan. Mn dan Zn dalam akar dan pucuk meningkat dengan meningkatnya kepekatan Mn dan Zn dalam larutan nutrien. Kepekatan Zn dalam akar dan pucuk dipertingkatkan dengan meningkatkan tahap Mn. Kepekatan Mn dalam pucuk tidak menunjukkan sebarang korelasi dengan kepekatan Zn dalam larutan nutrien tetapi kepekatan Mn dalam akar menurun dengan peningkatan aras Zn. Berat kering tanaman jagung muda paling rendah telah direkodkan di rawatan $Zn_{10}Mn_0$ disebabkan oleh kekurangan Mn. Jagung manis yang ditanam dalam kajian berpasu yang diberi semua kombinasi Zn pada tahap 0.0, 5.0, dan 10.0 mg kg^{-1} tanah dan P pada tahap 0.0, 50.0, 100.0, 200.0 mg kg^{-1} tanah sebagai $ZnSO_4.7H_2O$ dan KH_2PO_4, dan dituai 28 hari selepas pemindahan mendapati hasil bahan kering meningkat dengan bekalan P, manakala pemberian Zn tidak menunjukkan apa-apa kesan yang ketara ke atas parameter ini. Pengambilan Zn dan P dalam pucuk meningkat dengan meningkatnya pemberian Zn dan P kepada tanah. Kepekatan Zn dalam pucuk menurun dengan peningkatan bekalan P, tetapi kepekatan dan pengambilan P dipertingkatkan. Kekurangan Zn disebabkan oleh kadar P tinggi dalam kajian ini disebabkan oleh kesan pencairan. Peratusan P yang diserap daripada baja dikurangkan dengan peningkatan kadar Zn diberi, walaupun pengambilan P dalam pucuk tidak berubah.

© COPYRIGHT UPM

ACKNOWLEDGEMENTS

First and foremost, I would like to express profound gratitude to my supervisor Prof. Dr. Zaharah Abdul Rahman for giving me the opportunity and support along the way. I greatly appreciate the way she encouraged me to delve into complex issues and patiently allowed me to learn and work at my own pace. I am inspired by her attention to detail and her intense commitment to work. I have thoroughly enjoyed working with her and am thankful for her support both at an academic and personal level.

I am grateful to Prof. Dr. Hanafi Mohamed Musa and Assoc. Prof. Dr. Che Fauziah Ishak my committee members, also Ms. Zabedah Tumirin, our lab assistant, who helped me in my working time.

I am deeply indebted to my parents and parents in law who motivated me to pursue graduate studies at Malaysia, without their support I might not be able to come here.

I also want to thank my best friend and my wife Jasmine for her best efforts to support me in entire of my PhD academic period and my life.

I am very much indebted to my lovely sister in law, Mastaneh, who always helps me out during the “long journey”.

My sincere thanks go out to my siblings, Ardalan and Elmira, who made an excellent companion from childhood.

© COPYRIGHT UPM

I certify that a Thesis Examination Committee has met on 9 February 2015 to conduct the final examination of Amin Soltangheisi on his thesis entitled "Agronomic and Biochemical Expression of Zinc, Manganese and Phosphorus Interactions in Sweet Corn Plants (*Zea Mays* L. var. Saccharata (sturtev.) L. H. Bailey" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Shamshuddin Jusop, PhD
Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Aminuddin Hussin, PhD
Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Internal Examiner)

Yahya Awang, PhD
Associate Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Internal Examiner)

Md Jahiruddin, PhD
Professor
Bangladesh Agricultural University
Bangladesh
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 19 March 2015

© COPYRIGHT UPM

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Zaharah Abdul Rahman, PhD
Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Chairman)

Mohamed Hanafi Musa, PhD
Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

Che Fauziah Ishak, PhD
Professor
Faculty of Agriculture
Universiti Putra Malaysia
(Member)

BUJANG BIN KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

© COPYRIGHT UPM

Declaration by Graduate Student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at aby other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice Chancellor (Research and Innovation) before thesis is published (in the form of written, writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/ fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ______________________ Date: ______________

Name and Matric No: Amin Soltangheisi, GS31326

© COPYRIGHT UPM

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ____________________
Name of
Chairman of
Supervisory
Committee ____________________

Signature: ____________________
Name of
Member of
Supervisory
Committee ____________________

Signature: ____________________
Name of
Member of
Supervisory
Committee ____________________

© COPYRIGHT UPM

TABLE OF CONTENTS

Page

ABSTRACT i
ABSTRAKT iii
ACKNOWLEDGMENTS v
APPROVAL vi
DECLARATION viii
LIST OF TABLES xiii
LIST OF FIGURES xv
LIST OF ABBREVIATIONS xviii

CHAPTER

1 **INTRODUCTION** 1
- 1.1 General introduction 1
- 1.2 Justification 2
- 1.3 Objectives 2

2 **LITERATURE REVIEW** 4
- 2.1 Zinc 4
  - 2.1.1 Zinc cycle in soil-plant system 4
  - 2.1.2 Physiological function of zinc in plants 5
  - 2.1.3 Zinc deficiency in soils and plants 16
- 2.2 Phosphorus 22
  - 2.2.1 Phosphorus cycle in soil-plant system 22
  - 2.2.2 Physiological function of phosphorus in plants 27
  - 2.2.3 Phosphorus deficiency in soils and plants 31
- 2.3 Manganese 33
  - 2.3.1 Manganese cycle in soil-plant system 33
  - 2.3.2 Physiological function of manganese in plants 34
  - 2.3.3 Manganese toxicity and deficiency in soils and plants 39

3 **GENERAL MATERIALS AND METHODS** 41

4 **PHOSPHORUS, ZINC AND MANGANESE UPTAKE AND THEIR INTERACTION EFFECT ON DRY MATTER AND CHLOROPHYLL CONTENT OF SWEET CORN (*ZEA MAYS VAR. SACCHARATA*)** 44
- 4.1 Introduction 44
- 4.2 Materials and methods 46
  - 4.2.1 Experimental design 46

© COPYRIGHT UPM

4.2.2 Measurements 46
4.2.3 Calculations and statistical analysis 47
4.3 Results and discussion 47
4.4 Conclusion 56

5 **EFFECT OF ZINC AND PHOSPHORUS SUPPLY ON THE ACTIVITY OF CARBONIC ANHYDRASE AND THE ULTRASTRUCTURE OF CHLOROPLAST IN SWEET CORN (*ZEA MAYS VAR. SACCHARATA*)** 57
5.1 Introduction 57
5.2 Materials and methods 58
5.2.1 Experimental design 58
5.2.2 Measurements 58
5.2.3 Calculations and statistical analysis 60
5.3 Results and discussion 60
5.4 Conclusion 69

6 **INTERACTION EFFECTS OF ZINC, MANGANESE AND IRON ON GROWTH, UPTAKE RESPONSE, AND CHLOROPHYLL CONTENT OF SWEET CORN (*ZEA MAYS VAR. SACCHARATA*)** 68
6.1 Introduction 70
6.2 Materials and methods 71
6.2.1 Experimental design 71
6.2.2 Measurements 72
6.2.3 Calculations and statistical analysis 72
6.3 Results and discussion 72
6.4 Conclusion 86

7 **INTERACTION EFFECTS OF PHOSPHORUS AND ZINC ON THEIR UPTAKE AND ^{32}P ABSORPTION AND TRANSLOCATION IN SWEET CORN (*ZEA MAYS VAR. SACCHARATA*)** 87
7.1 Introduction 87
7.2 Materials and methods 88
7.2.1 Experimental design 88
7.2.2 Measurements 89
7.2.3 Calculations and statistical analysis 89
7.3 Results and discussion 90
7.4 Conclusion 100

8 **SUMMARY/ GENERAL CONCLUSION/ FUTURE RECOMMENDATION** 101

REFERENCES 103
APPENDIX 134
BIODATA OF STUDENT 141

© COPYRIGHT UPM

LIST OF PUBLICATIONS 142

© COPYRIGHT UPM

LIST OF TABLES

Table		Page
4.1	Dry weight (mg plant^{-1}) and total chlorophyll content (mg g^{-1} fresh weight) in sweet corn plants in nutrient solution with different P and Zn levels at 7 and 14 DAT	49
4.2	Leaf P/Zn concentration ratio and root/shoot Zn uptake ratio in sweet corn plants in nutrient solution with different P and Zn levels at 7 and 14 DAT	50
4.3	Zn uptake (µg plant^{-1}) and P uptake (µg plant^{-1}) by shoots in sweet corn plants in nutrient solution with different P and Zn levels at 7 and 14 DAT	51
4.4	Zn uptake (µg plant^{-1}) and P uptake (µg plant^{-1}) by roots in sweet corn plants in nutrient solution with different P and Zn levels at 7 and 14 DAT	52
5.1	Phosphorus (%) and zinc (µg g^{-1}) concentration and P/Zn ratio in leaves of sweet corn plants in nutrient solution with different Zn and P levels	62
5.2	Carbonic anhydrase activity (EU g^{-1} fresh tissue) and total chlorophyll content (mg g^{-1} fresh tissue) in leaves and average root diameter (mm) of sweet corn plants in nutrient solution with different Zn and P levels	64
6.1	Dry weight (mg plant^{-1}) and total chlorophyll content (mg g^{-1} fresh weight) of sweet corn plants in nutrient solution with different Zn and Mn levels	76
6.2	Mn and Zn concentration (µg g^{-1}) in leaves and roots, Mn/Zn ratio in leaves, root/shoot Mn uptake ratio, and root/shoot Zn uptake ratio of sweet corn plants in nutrient solution with different Zn and Mn levels	80

© COPYRIGHT UPM

6.3 Fe concentration (µg g^{-1}) in leaves and roots of sweet corn plants in nutrient solution with different Zn and Mn levels 84

7.1 Selected physic-chemical properties of the soil 90

7.2 Dry weight (mg $plant^{-1}$), chlorophyll a/b ratio, P (%) and Zn (µg g^{-1}) concentration in leaves, and P (mg $plant^{-1}$) and Zn (µg $plant^{-1}$) uptake of sweet corn plants in soil with different P and Zn levels 93

© COPYRIGHT UPM

LIST OF FIGURES

Figure		Page
2.1	Relationships between yield and nutrient concentration in plant tissue. (a) generalized relationship frequently found in plants as nutrient supply increases from deficient to toxic; (b) the C-shaped or Piper-Steenbjerg effect	9
2.2	Relationship between plant growth and nutrient concentration in the plant for diagnosis or predicting nutrient deficiency and toxicity	19
2.3	The phosphorus cycle in soils	24
2.4	The cycle of the oxidation states of manganese found in nature	35
4.1	The effect of Zn supply on Mn concentration in shoots of sweet corn plants	53
4.2	Relationship between Zn supplies and Mn concentration in roots of sweet corn plants at (a) 7 days and (b) 14 days after transplanting	54
4.3	Effect of P and Zn supplies on Mn concentration in roots of sweet corn plants at (a) 7 days and (b) 14 days after transplanting	55
5.1	Chloroplast from full-nutrient plant	66
5.2	Chloroplast from Zn_0P_{80} treatment	66
5.3	Chloroplast from $Zn_{20}P_0$ treatment	67
5.4	Chloroplast from $Zn_{20}P_{80}$ treatment	68

© COPYRIGHT UPM

5.5 Chloroplast from Zn_0P_0 treatment 69

6.1 Relationship between Mn supplies and Mn concentration in (a) roots and (b) shoots of sweet corn plants 73

6.2 Relationship between Zn supplies and Zn concentration in (a) roots and (b) shoots of sweet corn plants 74

6.3 Relationship between Mn supplies and Zn concentration in (a) roots and (b) shoots of sweet corn plants 75

6.4 Relationship between Zn supplies and Mn concentration in (a) roots and (b) shoots of sweet corn plants 77

6.5 Relationship between Zn supplies and root/shoot (a) Mn uptake ratio and (b) Zn uptake ratio of sweet corn plants 79

6.6 Relationship between Mn supplies and Fe concentration in shoots of sweet corn plans 81

6.7 Relationship between Zn supplies and Fe concentration in roots of sweet corn plants 82

7.1 Relationship between P supplies and dry weight in shoots of sweet corn plants 91

7.2 Relationship between P supplies and (a) Zn uptake and (b) Zn concentration in shoots of sweet corn plants 94

7.3 Relationship between P supplies and P uptake by shoots of sweet corn plants 95

7.4 Relationship between Zn supplies and (a) Zn uptake and (b) Zn concentration in shoots of sweet corn plants 96

© COPYRIGHT UPM

7.5 Relationship between P supplies and chlorophyll a/b ratio of sweet corn plants 97

7.6 Relationship between P supplies and %Pdff in shoots of sweet corn plants 98

7.7 Relationship between Zn supplies and %Pdff in shoots of sweet corn plants 99

7.8 Foliar symptoms of Zn deficiency 100

© COPYRIGHT UPM

LIST OF ABBREVIATIONS

^{o}C	Degree Celsius
%	Percent
ALA	Aminulevulinic Acid
ATA	Ammonia Tri-acetic Acid
ATP	Adenosine Triphosphate
CA	Carbonic Anhydrase
CEC	Cation Exchange Capacity
CIPR	Christmas Island Phosphate Rock
DAS	Days After Sowing
DAT	Days After Transplanting
DNA	Deoxyribonucleic Acid
DRIS	Diagnostic and Recommendation Integrated System
DTPA	Diethylene Triamine Pentaacetic Acid
e.g.	example gratia
EDTA	Ethylene Diamine Tetra-acetic Acid
EU	Enzyme Unit
fw	fresh weight
g	gram
h	hour
ICP	Inductively Coupled Plasma
kBq	kilobecquerel
kDa	kilodalton
kg	kilogram
L	Liter
M	Molar
mg	milligram
mL	milliliter
mm	millimeter
mM	millimolar
mRNA	Messenger Ribonucleic Acid

© COPYRIGHT UPM

nm	nanometer
OES	Optical Emission Spectrometry
OM	Organic Matter
Pdff	Phosphorus Derived From Fertilizer
PR	Phosphate Rock
RNA	Ribonucleic Acid
ROS	Reactive Oxygen Species
SA	Specific Activity
SOD	Superoxide Dismutase
SOM	Soil Organic Matter
TEM	Transmission Electron Microscopy
UPM	Universiti Putra Malaysia
YML	Youngest Mature Leaf
µg	microgram
µM	micromolar

© COPYRIGHT UPM

ABBREVIATIONS OF CHEMICAL MATERIALS

$CaCl_2$	Calcium chloride
$Ca(NO_3)_2$	Calcium nitrate
CO_2	Carbon dioxide
$CuSO_4$	Copper(II) sulfate
DMSO	Dimethyl Sulfoxide
EDTAFe	Iron(III) Ethylene Diamine Tetra-acetic Acid
$FePO_4$	Iron(III) phosphate
H_3BO_3	Boric acid
HCl	Hydrogen chloride
HNO_3	Nitric acid
K_2SO_4	Potassium sulfate
KH_2PO_4	Monopotassium phosphate
KCl	Potassium chloride
KOH	Potassium hydroxide
$MgCl_2$	Magnesium chloride
$MgSO_4$	Magnesium sulfate
MnO_2	Manganese dioxide
$MnSO_4$	Manganese(II) sulfate
$(NH_4)_6Mo_7O_{24}$	Ammonium heptamolybdate
P_2O_5	Phosphorus pentoxide
$Zn_3(PO_4)_2$	Zinc phosphate
$ZnSO_4.7H_2O$	Zinc sulfate heptahydrate

© COPYRIGHT UPM

ABBREVIATIONS OF STATISTICAL ANALYSIS

P	Probability
SAS	Statistical Analysis Software

© COPYRIGHT UPM

CHAPTER 1

INTRODUCTION

1.1. General introduction

Macro and micronutrients are required for normal growth, health, and reproduction of plants. Among the macronutrients, nitrogen, phosphorus, and potassium are consumed in large quantities. Micronutrients are needed in small quantities but they play an important role in plant's growth and health. Two of these essential micronutrients are zinc and manganese.

Practitioners are always searching for ways to achieve the optimum level of nutrition for horticultural crops but finding that is complicated because at least 12 essential nutrients are involved. Many factors influence the availability and uptake of these nutrients including environment, genetic differences, and nutrients interactions (May and Pritts, 1993).

Balanced supply of essential nutrients is one of the most important factors in increasing crop yields. In crop plants, the nutrient interactions are generally measured in terms of growth response and change in concentration of nutrients. Upon addition of two nutrients, an increase in crop yield that is more than adding only one, shows a positive interaction (synergistic). Similarly, if adding the two nutrients together produced less yield as compared to individual ones, the interactions are negative (antagonistic). When there is no change, there is no interaction. All the three interactions among essential plant nutrients have been reported. However, most interactions are complex. A nutrient has interaction simultaneously with more than one nutrient. This may induce deficiencies, toxicities, modified growth responses, and/or modified nutrient composition (Fageria, 2001).

Interaction between nutrients in crop plants occurs when the supply of one nutrient affects the absorption and utilization of other nutrients. This type of interaction is most common when one nutrient is in excess concentration in the growth medium. Nutrient interactions can occur at the root surface or within the plant and can be classified into two major categories. In the first category are interactions which occur between ions because the ions are able to form a chemical bond. Interactions in this case are due to the formation of precipitates or complexes. For example, this type of interaction occurs where the liming of acid soils decrease the concentration of almost all micronutrients except molybdenum. But this decrease varies from nutrient to nutrient. For example, Cu is more strongly complexed by soluble organic matter than Zn, and effects of increasing soil pH are more marked on Zn uptake than Cu uptake by plants. The second form of interaction is between ions whose chemical properties are sufficiently similar that they compete for site of adsorption, absorption, transport, and function on plant root surfaces or within plant tissues. Such interactions are more common between nutrients of similar

© COPYRIGHT UPM

size, charge, geometry of coordination, and electronic configuration. This type of interaction is common among Ca^{2+}, Mg^{2+}, K^+, and Na^+ (Fageria, 2001).

Hiatt and Leggett (1974) suggested that cation-cation and anion-anion interactions occur mostly at the membrane level and are primarily of a competitive nature. Cation-anion interactions occur at both the membrane and in cellular processes after absorption. These cellular interactions are less understood. Epstein (1972) pointed out that the cation content of plant material is dependent on both the availability of the particular cation and the presence or absence of other caitons in the growth medium. Generally an excess of one cation in the nutrient medium reduces the net uptake of other cations, whereas the sum of cations in the plant tissue often remains nearly constant. This phenomenon is called cation antagonism.

1.2. Justification

While Malaysian farmers apply N, P and K fertilizers widely, it is found that the application of micronutrients, such as Zn is not a usual practiced (Liew, 2010). Zinc deficiency is found in crops due to intensive cropping, loss of fertile topsoil and losses of nutrients through leaching. Low levels of trace elements are expected in the oldest landscapes in zones of high rainfall and temperature, and where trace element concentrations in parent materials are originally low thus Malaysian soils are Zn deficient (White and Zasoski, 1999). The presence of Zn deficiency renders it impossible for the plant to gain maximum benefit from NPK fertilizer applications. Zn has been categorized as essential and plants cannot complete their life cycle in the absence of Zn (Marschner, 1996). The application of solely NPK fertilizers is no longer practical due to the continuous removal of micronutrients after harvesting, as well as losses due to leaching or surface runoffs. As Zn and P can act antagonistically with one another, the amount of P application is important because excessive P can cause Zn deficiency in plant tissue. Information on the photosynthetic response of corn plants to Zn deficiency or to P-induced Zn deficiency is absent and the mechanism which Zn and P interaction affects chlorophyll content is unknown. The response of roots to Zn and P interaction is also unknown. The best amount of P and Zn fertilizer in corn production is also investigated in this research. Manganese is one of the most important elements in Malaysian soils. The interaction of different levels of Mn and Zn are also investigated because Mn can directly affect the Zn concentration in plants and Malaysian soils have variable amount of Mn in soils from place to place.

1.3. Objectives

Four major experiments were carried out for this thesis with the overall objectives of:

1) To investigate the effects of Zn-P interaction on the chlorophyll content, nutrients uptake, chloroplast structure, carbonic anhydrase activity, and root characteristics at different vegetative growth stages of sweet corn plants.

2) To investigate the mechanism of P-induced Zn deficiency in sweet corn plants.

3) To evaluate the effect of P-Zn interaction on dry matter yield and ^{32}P absorption of sweet corn plants in acid soils.

4) To investigate the effects of Zn-Mn interaction on the chlorophyll content, nutrients uptake, and root characteristics at different vegetative stages in sweet corn plants.

© COPYRIGHT UPM

REFERENCES

A.O.A.C., (1984). Official Methods of Analysis, 14th Edition. Association of Official Analytical Chemist, Washington D.C.

Abadía, J., F. Morales and A. Abadía (1999). Photosystem II efficiency in low chlorophyll, iron-deficient leaves. Plant Soil, 215(2): 183-192.

Abdul Rida, A. M. M. and M. B. Bouché (1997). Heavy metal linkages with mineral, organic and living soil compartments. Soil Biol. Biochem., 29(3): 649-655.

Adriano, D. C., G. M. Paulsen and L. S. Murphy (1971). Phosphorus-iron and phosphorus-zinc relationships in corn (*Zea mays* L.) seedlings as affected by mineral nutrition. Agron. J., 63(1): 36-39.

Adiloglu, S. (2006). The effect of increasing nitrogen and zinc doses on the iron, copper and manganese contents of maize plants in calcareous and zinc deficient soils. Asian J. Plant Sci., 5(3): 504-507.

Agarwala, S. C., C. Chatterjee and N. Nautiyal (1986). Effect of manganese supply on the physiological availability of iron in rice plants grown in sand culture. Soil Sci. Plant Nutr., 32(2): 169-178.

Ajakaiye, C. O. (1979). Effect of phosphorus on growth and iron nutrition of millet and sorghum. Plant Soil, 51(4): 551-561.

Alam, S. M. and A. Shereen (2002). Effect of Different Levels of Zinc and Phosphorus on Growth and Chlorophyll Content of Wheat. Asian J. Plant Sci., 1(4): 364-366.

Alloway, B. J. and B. J. Alloway (Eds.). (1995). Heavy metals in soils. Environ. Pollut., 22.

Alloway, B. J. (2004). *Zinc in Soils and Crop Nutrition*. Brussels, Belgium: International Zinc Association.

Alou, M. M. (1989). Effects of phosphorus and zinc nutrition and composition of the corn root and plasma membrane in relation to vesicular–arbuscular mycorrhiza formation, PhD dissertation, University of California Riverside.

Ambler, J. E., J. C. Brown and H. G. Gauch (1970). Effect of zinc on translocation of iron in soybean plants. Plant Physiol., 46(2): 320-323.

Anderson, G. (1967). Nucleic acids, derivatives, and organic phosphates. Soil biochem., 1: 67-90.

Anderson, D. L., W. R. Kussow and R. B. Corey (1985). Phosphate rock dissolution in soil: Indications from plant growth studies. Soil Sci. Soc. Am. J., 49(4): 918-925.

Andrew, C. S., A. D. Johnson and H. P. Haydock (1981). The diagnosis of zinc deficiency and effect of zinc on the growth and chemical composition of some tropical and sub-tropical legumes. Comm. Soil Sci. Plant Anal. 12: 1-18.

Armour, J.D. and R. F. Brennan (1999). Zinc. In *Soil Analysis: An Interpretation Manual*. Eds. K.I. Peverill, L. A. Sparrow and D. J. Reuter. pp. 281-285. CSIRO Publishing, Australia.

Arnon, D. I. (1949). Copper enzymes in isolated chloroplasts. Polyphenoloxidase in Beta vulgaris. Plant physiol., 24(1): 1.

Atkins, C. A., B. D. Patterson and D. Graham (1972) Plant carbonic anhydrase I. Distribution of types among species. Plant Physiol. 50: 214–217.

Bar-Akiva, A. and R. Lavon (1969). Carbonic anhydrase activity as an indicator of zinc deficiency in citrus leaves. J. Hort. Sci., 359-362.

Barben, S. A., B. G. Hopkins, V. D. Jolley, B. L. Webb and B. A. Nichols (2010). Phosphorus and manganese interactions and their relationships with zinc in chelator-buffered solution grown Russet Burbank potato. J. Plant Nutr., 33(5): 752-769.

Barben, S. A., B. G. Hopkins, V. D. Jolley, B. L. Webb and B. A. Nichols (2010). Phosphorus and zinc interactions in chelator-buffered solution grown Russet Burbank potato. J. Plant Nutr., 33(4): 587-601.

Barben, S. A., B. G. Hopkins, V. D. Jolley, B. L. Webb, B. A. Nichols and E. A. Buxton (2011). Zinc, manganese and phosphorus interrelationships and their effects on iron and copper in chelator-buffered solution grown russet burbank potato. J. Plant Nutr., 34(8): 1144-1163.

Barber, S. A. (1980). Twenty-five years of phosphate and potassium fertilization of a crop rotation. Fert. Res., 1(1): 29-36.

Barber, S. A. (1995). *Soil Nutrient Bioavailability: A Mechanistic Approach*. John Wiley and Sons.

Barber, S. A., J. M. Walker and E. H. Vasey (1963). Mechanisms for movement of plant nutrients from soil and fertilizer to plant root. J. Agr. Food Chem., 11(3): 204-207.

Barrow, N. J. (1986). Testing a mechanistic model. IV. Describing the effects of pH on zinc retention by soils. J. Soil Sci., 37(2): 295-302.

Bates, T. E. (1971) Factors affecting critical nutrient concentrations in plants and their evaluation: a review. Soil Sci., 112: 1126-1130.

Batten, G. D., I. F. Wardlaw and M. J. Aston (1986). Growth and the distribution of phosphorus in wheat developed under various phosphorus and temperature regimes. Crop Pasture Sci., 37(5): 459-469.

Beaton, J. D. and W. L. Nelson (2005). *Soil Fertility and Fertilizers: An Introduction to Nutrient Management* (Vol. 515). Upper Saddle River, NJ: Pearson Prentice Hall.

Beaufils, E. R. (1973) Diagnosis and recommendation integrated system (DRIS). Soil Sci. Bull. 1, (Uni. Of Natal: Natal, Sth. Africa)

Bell, P. F., R. L. Chaney and J. S. Angle (1991). Free metal activity and total metal concentration as indices of micronutrient availability to barley (*Hordeum vulgare* L. cv. Klages). Plant Soil, 130: 51-62.

Bell, R. W. (2000) Temporary nutrient deficiency- a difficult case for diagnosis and prognosis by plant analysis. Comm. Soil Sci. Plant Anal., 31: 1847-1861.

Bell, R. W., G. S. Kirk, D. Plaskett and J. F. Loneragan (1990). Diagnosis of zinc deficiency in peanut (*Arachis hypogaeea*) by plant analysis. Comm. Soil Sci. Plant Anal., 21: 273-285.

Bettger, W. J. and B. L. O'Dell (1981). A critical physiological role of zinc in the structure and function of biomembranes. Life sci., 28(13): 1425-1438.

Bieleski, R. L. (1973). Phosphate pools, phosphate transport, and phosphate availability. Ann. Rev. Plant Physiol., 24(1): 225-252.

Bieleski, R. L. and I. B. Ferguson (1983). Physiology and metabolism of phosphate and its compounds. In *Inorganic Plant Nutrition* (pp. 422-449). Springer Berlin Heidelberg.

Bingham, F. T. and M. J. Garber (1960). Solubility and availability of micronutrients in relation to phosphorus fertilization. Soil Sci. Soc. Am. J., 24(3): 209-213.

Blamey, F. P. C., D. C. Joyce, D. G. Edwards and C. J. Asher (1986). Role of trichomes in sunflower tolerance to manganese toxicity. Plant Soil, 91(2): 171-180.

Blamey, F. P. C., D. G. W. Edwards and C. J. Asher (1987). Nutritional disorders of sunflower. Dept. Agriculture, Univ. Queensland, Australia, 72 pp.

Boawn, L. C. and G. E. Leggett (1964). Phosphorus and zinc concentrations in Russet Burbank potato tissues in relation to development of zinc deficiency symptoms. Soil Sci. Soc. Am. J., 28(2), 229-232.

Boawn, L. C. and J. C. Brown (1968). Further evidence for a P-Zn imbalance in plants. Soil Sci. Soc. Am. J., 32(1): 94-97.

Boawn, L. C., F. G. Viets, C. L. Crawford and J. L. Nelson (1960). Effect of nitrogen carrier, nitrogen rate, zinc rate, and soil pH on zinc uptake by sorghum, potatoes, and sugar beets. Soil Sci., 90: 329-337.

Boawn, L. C., J. R. Viets and C. L. Crawford (1957). Plant utilization of zinc from various types of zinc compounds and fertilizer materials. Soil Sci., 83(3): 219-228.

Bolan, N. S. and M. J. Hedley (1990). Dissolution of phosphate rocks in soils. 2. Effect of pH on the dissolution and plant availability of phosphate rock in soil with pH dependent charge. Fert. Res., 24(3): 125-134.

Bolland, M. D. A. (1998). Phosphorus. In ‘Soilguide: a handbook for understanding and managing agricultural soils’.(Ed. G Moore) pp. 168–175.*Agriculture Western Australia Bulletin*, *4343*.

Bolland, M. D. A., A. M. Posner and J. P. Quirk (1977). Zinc adsorption by goethite in the absence and presence of phosphate. Soil Res., 15(3): 279-286.

Bould, C., E. J. Hewitt and P. Needham (Eds.) (1983). Diagnosis of Mineral Disorders in Plants. Vol. 1. Principles. (HMSO: London, UK)

Bounma, T. J., K. L. Nielsen and B. Koutstaal (2000). Sample preparation and scanning protocol for competensed analysis of root length and diameter. Plant Soil, 218: 185-196.

Bowen, J. E. (1969). Absorption of copper, zinc, and manganese by sugarcane leaf tissue. Plant physiol., 44(2): 255-261.

Bowen, J. E. (1972). Manganese-silicon interaction and its effect on growth of Sudan grass. Plant Soil, 37(3): 577-588.

Bowen, G. D., M. F. Skinner and D. I. Bevege (1974). Zinc uptake by mycorrhizal and uninfected roots of *Pinus radiata* and *Auracaria cunninghamii*. Soil Biol. Biochem., 6: 141-144.

Brady, N. C. and R. R. Weil (2010). *Elements of the Nature and Properties of Soils* (p. 383). Upper Saddle River, NJ: Pearson Educational International.

Brennan, R. F. and J. W. Gartrell (1981) Zinc requirements of crops and pastures. Our Land, 13: 10-13.

Brennan, R. F. and M. D. A. Bolland (2002). Relative effectiveness of soil-applied zinc for four crop species. Anim. Prod. Sci., 42(7): 985-993.

Brennan, R. F., J. D. Armour and D. J. Reuter (1993). Diagnosis of zinc deficiency. In *Zinc in Soils and Plants* (pp. 167-181). Springer Netherlands.

Brown, A. L., B. A. Krantz and J. L. Eddings (1970). Zinc-phosphorus interactions as measured by plant response and soil analysis. Soil Sci., 110(6): 415-420.

Brown, J. C. (1963). Interactions involving nutrient elements. Annu. Rev. Plant Physiol., 14(1): 93-106.

Brown, J. C. and L. O. Tiffin (1962). Zinc deficiency and iron chlorosis dependent on the plant species and nutrient-element balance in Tulare clay. Agron. J., 54(4): 356-358.

Brown, P. H., I. Cakmak and Q. Zhang (1993). Form and function of zinc plants. In *Zinc in soils and plants* (pp. 93-106). Springer Netherlands.

Burleson, C. A. and N. R. Page (1967). Phosphorus and zinc interactions in flax. Soil Sci. Soc. Am. J., 31(4): 510-513.

Cakmak, I. (2002). Plant nutrition research: Priorities to meet human needs for food in sustainable ways. In *Progress in Plant Nutrition: Plenary Lectures of the XIV International Plant Nutrition Colloquium* (pp. 3-24). Springer Netherlands.

Cakmak, I. and H. Marschner (1987). Mechanism of phosphorus-induced zinc deficiency in cotton. III. Changes in physiological availability of zinc in plants. Physiol. Plant., 70(1): 13-20.

Cakmak, I. and H. Marschner (1993). Effect of zinc nutritional status on activities of superoxide radical and hydrogen peroxide scavenging enzymes in bean leaves. Plant Soil, 155(1): 127-130.

Cakmak, I. and H. Marschner (2006). Mechanism of phosphorus-induced zinc deficiency in cotton. III. Changes in physiological availability of zinc in plants. Physiol. Plant., 70(1): 13-20.

Cakmak, I., H. Marschner and F. Bangerth (1989). Effect of zinc nutrition status on growth, protein metabolism and level of indole-3 acetic acid and other phytohormones in bean (*Phaseolus vulgaris* L.). J. Exp. Bot., 40(3): 405-412.

Cakmak, I., M. Kalaycı, H. Ekiz, H. J. Braun, Y. Kılınç and A. Yılmaz (1999). Zinc deficiency as a practical problem in plant and human nutrition in Turkey: a NATO-science for stability project. Field Crop. Res., 60(1): 175-188.

Carroll, M.D. and J. F. Loneragan (1968). Response of plant species to concentrations of zinc in solution. I. Growth and zinc content of plants. Aust. J. Agric. Res., 19: 859-68.

Carroll, M.D. and J. F. Loneragan (1969) Response of plant species to concentrations of zinc in solution. II. Rates of zinc absorption and their relation to growth. Aust. J. Agric. Res., 20: 457-463.

Cathcart, J. B. (1980). World phosphate reserves and resources. *The role of phosphorus in agriculture*, (theroleofphosph), 1-18.

Celi, L. and E. Barberis (2005). Abiotic stabilization of organic phosphorus in the environment. *Organic phosphorus in the environment*, 113-132.

Chandler, W.H., D. R. Hoaglands and P. L. Hibbard (1931). Little leaf or rosette in fruit trees. Proc. Am. Soc. Hort. Sci., 28: 556-560.

Chapman, H.D. (1966). Zinc. In 'Diagnostic Criteria for Plant and Soils'. (Ed. HD Chapman) pp. 484-499. (Uni. of Calif., Div. Agric. Sci.: Berkeley, USA)

Charlton, W. A. (1996). Lateral root initiation. In 'Plant roots: the hidden half.' (Eds Y Waisel, A Eshel and U Kfkafa) pp. 149–173. (Marcel Dekker Inc.: New York).

Chaudhry, F. M. and J. F. Loneragan (1972). Zinc absorption by wheat seedlings: II. Inhibition by hydrogen ions and by micronutrient cations. Soil Sci. Soc. Am. J., 36(2), 327-331.

Chaudhry, F.M., J. F. Loneragan, A. Latif and R. H. Qureshi (1973). Zinc-copper antagonism in the nutrition of rice (*Oryza sativa* L.). Plant Soil, 38: 573-580.

Chien, S. H. (1979). Dissolution of phosphate rock in acid soils as influenced by nitrogen and potassium fertilizers. Soil Sci., 127(6): 371-376.

Chinnery, L. E. and C. P. Harding (1980). The effect of ferrous iron on the uptake of manganese by *Juncus effusus* L. Ann. Bot., 46(4): 409-412.

Chou, F. I. and S. T. Tan (1990). Manganese (II) induces cell division and increases in superoxide dismutase and catalase activities in an aging deinococcal culture. J. Bacteriol., 172(4): 2029-2035.

Christensen, N. W. (1972). New hypothesis to explain phosphorus-induced zinc deficiencies. Ph.D. dissertation, Oregon State University, Corvallis, OR, USA. Dissertation Abstract 72-05086; Dissertation Abstract International 32B: 4348.

Christensen, N. W. and T. L. Jackson (1981). Potential for phosphorus toxicity in zinc-stressed corn and potato. Soil Sci. Soc. Am. J., 45(5): 904-909.

Chvapil, M. (1973). New aspects in the biological role of zinc: A stabilizer of macromolecules and biological membranes. Life Sci., 13: 1041-1049.

Clare, A. B., G. Ronald, M. Laren, W. R. Andrew and S. S. Roger (1995). Kinetic of cadmium and cobalt description from iron and manganese oxides. Soil Sci. Soc. Am. J., 59:778-785.

Clark, R. B. (1990). Physiology of cereals for mineral nutrient uptake, use and efficiency. Crops as enhancers of nutrient use, 131-209.

Clarkson, D. T. and J. Sanderson (1969). The uptake of a polyvalent cation and its distribution in the root apices of Allium cepa: Tracer and autoradiographic studies. Planta, 89(2): 136-154.

Comerford, N. B. (1998). Soil phosphorus bioavailability. Curr. Top. Plant Physiol., 19: 136-147.

Corley, R. H. V. and P. B. H. Tinker (2008). *The Oil Palm. John Wiley and Sons.*

Craswell, E. T., J. F. Loneragan and P. Keerati-Kasikorn (1987). Mineral constraints to food legume crop production in Asia. *Food Legume Improvement for Asian Farming Systems. Eds. ES Wallis and DE Byth*, 99-111.

Cumbus, I. P., D. J. Hornsey and L. W. Robinson (1977). The influence of phosphorus, zinc and manganese on absorption and translocation of iron in watercress. Plant Soil, 48(3): 651-660.

Curtin, D. and H. P. W. Rostad (1997). Cation exchange and buffer potential of Saskatchewan soils estimated from texture, organic matter and pH. Can. J. Soil Sci., 77(4): 621-626.

Dalal, R. C. (1977). Soil organic phosphorus. Adv. Agron, 29: 83-117.

Das, K., R. Dang, T. N. Shivananda and P. Sur (2005). Interaction between phosphorus and zinc on the biomass yield and yield attributes of the medicinal plant stevia *(Stevia rebaudiana)*. Scientific World J., 5: 390-395.

De Varennes, A., J. P. Carneiro and M. J. Goss (2001). Characterization of manganese toxicity in two species of annual medics. J. Plant Nutr., 24(12): 1947-1955.

Dell, B. and S. A. Wilson (1989). Zinc nutrition and leaf carbonic anhydrase activity of *Eucalyptus maculata* seedlings and *Trifolium subterraneum*. Plant Soil, 113(2): 287-290.

Dixon, J. B. and S. B. Weed (1989). *Minerals in Soil Environment.* Second Edition. Soil Sci. Soc. Am., Inc. USA.

Dobermann, A. and T. Fairhurst (2000). *Rice: Nutrient Disorders & Nutrient Management* (Vol. 1). Int. Rice Res. Inst..

Dow, A. I. and S. Roberts (1982). Proposal: Critical nutrient ranges for crop diagnosis. Agron. J., 74(2): 401-403.

Dučić, T. and A. Polle (2007). Manganese toxicity in two varieties of Douglas fir *(Pseudotsuga menziesii var. viridis and glauca)* seedlings as affected by phosphorus supply. Funct. Plant Biol., 34(1): 31-40.

Duguma, B., B. T. Kang and D. U. U. Okeli (1988) Effect of liming and phosphorus application on performance of *Leucaena leucoccephala* in acid soils. Plant Soil, 110: 57 – 61.

Dwivedi, R.S. and N. S. Randahwa (1974). Evaluation of a rapid test for the hidden hunger of zinc in plants. Plant Soil, 112: 445-51.

Dwivedi, R.S. and P. N. Takkar (1974). Ribonuclease activity as an index of hidden hunger of zinc in crops. Plant Soil, 112: 173-181.

Dwivedi, R. S., N. S. Randhawa and R. L. Bansal (1975). Phosphorus-zinc interaction, 1: sites of immobilization of zinc in maize at a high level of phosphorus. Plant Soil, 43(1): 639-648.

El-Fouly, M. M., O. A. Nofal and Z. M. Mobarak (2001). Effects of soil treatment with iron, manganese and zinc on growth and micronutrient uptake of sunflower plants grown in high-pH soil. J. Agron. Crop sci., 186(4): 245-251.

El-Jaoual, T. and D. A. Cox (1998). Manganese toxicity in plants. J. Plant Nutr., 21(2): 353-386.

Ellis, R., J. F. Davis and D. L. Thurlow (1964). Zinc availability in calcareous Michigan soils as influenced by phosphorus level and temperature. Soil Sci. Soc. Am. J., 28(1): 83-86.

Epstein, E. (1972). *Mineral Nutrition of Plants: principles and perspectives*. New York, John Wiley, pp. 357-362.

Fageria, N. K. (1992). *Maximizing crop yields*. CRC Press.

Fageria, N. K. (2004). Dry matter yield and nutrient uptake by lowland rice at different growth stages. J. Plant Nutr., 27(6): 947-958.

Fageria, N. K., V. C. Baligar and R. B. Clark (2002). Micronutrients in crop production. Adv. Agron., 77: 185-268.

Fageria, V. D. (2001). Nutrient interactions in crop plants. J. Plant Nutr., 24(8): 1269-1290.

Farrah, H., D. Hatton and W. F. Pickering (1980). The affinity of metal ions for clay surfaces. Chem. Geol., 28: 55-68.

Farah, M. A. and M. F. Soliman (1986). Zinc-phosphorus interaction in wheat plants. Agrochimica, 30 (6): 419-426.

Foth, H. D. and B. G. Ellis (1997). Soil fertility. Wiley, New York, (Ed. 2).

Fox, R. L. (1981). External phosphorus requirements of crops. In 'Chemistry in the soil environment.' (Ed. RH Dowdy) pp. 223-239. (American Society of Agronomy: Madison, USA).

Fox, T. C. and M. L. Guerinot (1998). Molecular biology of cation transport in plants. Annu. Rev. Plant Biol., 49(1): 669-696.

Foyer, C. and C. Spencer (1986). The relationship between phosphate status and photosynthesis in leaves. Planta, 167(3): 369-375.

Francois, L. E. and E. V. Maas (1994). Crop response and management on salt-affected soils. *Handbook of plant and crop stress*, 149-181.

Fredeen, A. L., I. M. Rao and N. Terry (1989). Influence of phosphorus nutrition on growth and carbon partitioning in Glycine max. Plant Physiol., 89(1): 225-230.

Friesen, D. K., A. S. R. Juo and M. H. Miller (1980). Liming and lime-phosphorus-zinc interactions in two Nigerian Ultisols: I. Interactions in the soil. Soil Sci. Soc. Am. J., 44(6): 1221-1226.

Fridovich, I. (1975). Superoxide dismutases. Annu. Rev. Biochem., 44(1): 147-159.

Fukaki, H. and M. Tasaka (2009). Hormone interactions during lateral root formation. Plant Mol. Biol., 69(4): 437-449.

Furihata, T., M. Suzuki and H. Sakurai (1992). Kinetic characterization of two phosphate uptake systems with different affinities in suspension-cultured Catharanthus roseus protoplasts. Plant Cell Physiol., 33(8): 1151-1157.

Gangwar, M. R., M. S. Gangwar and P. C. Srivastava (1989). Effect of Zn-Cu ineraction on photosynthetic pigments and some enzyme activities in the foliage of rice. Oryza, 26: 156-161.

Gartrell, J.W. (1969) The effects of copper and zinc on newly cleared land in the wheatbelt of Western Australia. West. Aust. Dept. Agric. Tech. Bull. No. 3. (Dept. Agric. West. Aust.: Sth. Perth, Aust.)

Ge, Z., G. Rubio and J. P. Lynch (2000). The importance of root gravitropism for inter-root competition and phosphorus acquisition efficiency: results from a geometric simulation model. Plant Soil, 218(1-2): 159-171.

Gianquinto, G., A. Abu-Rayyan, L. Di Tola, D. Piccotino and B. Pezzarossa (2000). Interaction effects of phosphorus and zinc on photosynthesis, growth and yield of dwarf bean grown in two environments. Plant Soil, 220(1): 219-228.

Gibson, T. S. and D. R. Leece (1981). Estimation of physiologically active zinc in maize by biochemical assay. Plant Soil, 63(3): 395-406.

Gill, M. A., S. Kanwal and T. Aziz (2004). Differences in phosphorus-zinc interaction among sunflower (*Helianthusannuus* L.) brassica (*Brassica napus* L.) and maize (*Zea mays* L.). Pak. J. Agri. Sci., 41.

Giller, K. E., E. Witter and S. P. Mcgrath (1998). Toxicity of heavy metals to microorganisms and microbial processes in agricultural soils: a review. Soil Biol. Biochem., 30(10): 1389-1414.

Giordano, P. M. and J. J. Mortvedt (1969). Phosphorus availability to corn as affected by granulating manganese with ortho-and pyrophosphate fertilizers. Soil Sci. Soc. Am. J., 33(3): 460-463.

Giordano, P. M. and J. J. Mortvedt (1971). Effect of substrate Zn level on distribution of photo-assimilated C14 in maize and bean plants. Plant Soil, 35(1-3): 193-196.

Giordano, P. M., J. C. Noggle and J. J. Mortvedt (1974). Zinc uptake by rice, as affected by metabolic inhibitors and competing cations. Plant Soil, 41(3): 637-646.

Glass, A. D. M. and M. Y. Siddiqi (1984). Control of nutrient uptake rates in relation to the inorganic composition of plants. Adv. Plant Nutr., 1: 103-147.

Goldschmidt, V. M. (1954). Geochemistry. Soil Sci., 78(2), 156.

Goss, M. J. and M. J. G. P. R. Carvalho (1992). Manganese toxicity: The significance of magnesium for the sensitivity of wheat plants. Plant Soil, 139(1): 91-98.

Graham, R. D. and M. L. Reed (1991). Carbonic anhydrase and the regulation of photosynthesis. Nature New Biol., 231: 81-83.

Grundon, N. J. (2006). Nutrient deficiency and toxicity symptoms. Encyclopedia Soil Sci., 2: 1144.

Grundon, N. J., D. G. Edwards, P. N. Takkar, C. J. Asher and R. B. Clark (1987). Nutritional disorders of grain sorghum. ACIAR, Australia. 88 p.

Grusak, M. A., J. N. Pearson and E. Marentes (1999). The physiology of micronutrient homeostasis in field crops. Field Crop Res., 60(1): 41-56.

Gunes, A., M. Alpaslan and A. Inal (1998). Critical nutrient concentrations and antagonistic and synergistic relationships among the nutrients of NFT-grown young tomato plants. J. Plant Nutr., 21(10): 2035-2047.

Gutknecht, J. (1961). Mechanisms of radioactive zinc uptake by Ulva lactuca. Linnol. Oceangr., 6: 426-431.

Gutknecht, J. (1963). Radioactive zinc uptake by benthic marine algae. Linnol. Oceangr., 8: 31-38.

Haldar, M. and L. N. Mandal (1981). Effect of phosphorus and zinc on the growth and phosphorus, zinc, copper, iron and manganese nutrition of rice. Plant Soil, 59(3): 415-425.

Hall, J. L. and L. E. Williams (2003). Transition metal transporters in plants. J. Exp. Bot., 54(393): 2601-2613.

Hallmark, W.B., R. B. Beverly, M. B. Parker, J. F. Adam, F. C. Boswell, K. Ohki, L. M. Shuman and D. O. Wilson (1989). Evaluation of soybean zinc and manganese requirements by the M-DRIS and sufficiency range methods. Agron. J., 81: 770-776.

Halvorson, A.D. and W. L. Lindsay (1977) The critical Zn^{2+} concentration for corn and the non-absorption of chelated zinc. Soil Sci. Soc. Am. J., 41: 531-534.

Hamilton, M.A., D. T. Westermann and D. W. James (1993). Factors affecting zinc uptake in cropping systems. Soil Sci. Soc. Am. J., 57: 1310-1315.

Hanafi, M. M., J. K. Syers and N. S. Bolan (1992). Leaching effect on the dissolution of two phosphate rocks in acid soils. Soil Sci. Soc. Am. J., 56(4): 1325-1330.

Hardie, D. G. (1991). *Biochemical Messengers: Hormones, Neurotransmitters and Growth Factors*. Chapman and Hall, London).

Hatch, M. D. and J. N. Burnell (1990). Carbonic anhydrase activity in leaves and its role in the first step of C4 photosynthesis. Plant Physiol., 93(2): 825-828.

Hawf, L. R. and W. E. Schmid (1967). Uptake and translocation of zinc by intact plants. Plant Soil, 27(2): 249-260.

Haynes, R. J. and T. E. Ludecke (1981). Effect of lime and phosphorus applications on concentrations of available nutrients and on P, Al and Mn uptake by two pasture legumes in an acid soil. Plant Soil, 62(1): 117-128.

Hedley, M. J., R. E. White and P. H. Nye (1982). Plant-induced changes in the rhizosphere of rape (*Brassica Napus var. Emerald*) seedlings. New Phytol., 91(1): 45-56.

Heenan, D. P. and L. C. Campbell (1980). Transport and distribution of manganese in two cultivars of soybean (*Glycine max* L.). Crop Pasture Sci., 31(5): 943-949.

Helyar K. R. and G. H. Price (1999). Making recommendations based on soil tests. In 'Soil analysis: an interpretation manual.' (Eds KI Peverill, LA Sparrow and DJ Reuter). (CSIRO Publishing: Melbourne, Australia).

Hewitt, E. J. (1984). The effects of mineral deficiencies and excesses on growth and composition. In Late Bould, C., Hewitt, E. J., Needham, P., Robinson, J. B. D.

© COPYRIGHT UPM

(Eds), Diagnosis of mineral disorders in plants, Vol. I. Principals. HMSO, London, pp. 54-110.

Hiatt, A. J. and H. F. Massey (1958). Zinc levels in relation to zinc content and growth of corn. Agron. J., 50(1): 22-24.

Hiatt, A. J. and J. E. Leggett (1974). Ionic interactions and antagonisms in plants. Proc Plant Root Environ.

Himes, F.L., S. A. Barber (1957). Chelating ability of soil organic matter. Soil Sci. Soc. Am. Proc., 21: 368-373.

Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. Plant Soil, 237(2): 173-195.

Hocking, P. J. and J. S. Pate (1978). Accumulation and distribution of mineral elements in the annual lupins *Lupinus albus* L. and *Lupinus angustifolius* L. Crop Pasture Sci., 29(2): 267-280.

Hodgson, J. F. (1963). Chemistry of the micronutrient elements in soils. Adv. Agron., 15: 119-159.

Holford, I. C. R. (1997). Soil phosphorus: its measurement, and its uptake by plants. Aust. J. Soil Res., 35(2): 227-240.

Hopkins, B. G., D. A. Whitney, R. E. Lamond and V. D. Jolley (1998). Phytosiderophore release by Sorghum, wheat, and corn under zinc deficiency. J. Plant Nutr., 21(12): 2623-2637.

Horiguchi, T. (1987). Mechanism of manganese toxicity and tolerance of plants: II. Deposition of oxidized manganese in plant tissues. Soil Sci. Plant Nutr., 33(4): 595-606.

Horovitz, C. T. (2000). *Biochemistry of Scandium and Yttrium, Part 2: Biochemistry and Applications:* In *Biochemistry and Physiology of Scandium and Yttrium*, pp. 39-163, Springer, New York, NY, USA, 2000.

Horst, W. J. and H. Marschner (1978). Effect of silicon on manganese tolerance of bean plants (*Phaseolus vulgaris* L.). Plant Soil, 50(1-3): 287-303.

Huang, C., S. J. Barker, P. Langridge, F. W. Smith and R. D. Graham (2000). Zinc deficiency up-regulates expression of high-affinity phosphate transporter genes in both phosphate-sufficient and-deficient barley roots. Plant Physiol.,124(1): 415-422.

Hue, N. V. (1992). Correcting soil acidity of a highly weathered ultisol with chicken manure and sewage sludge. Communications in Soil Sci. Plant Anal., 23(3-4): 241-264.

Imtiaz, M., B. J. Alloway, K. H. Shah, S. H. Siddiqui, M. Y. Memon, M. Aslam and P. Khan (2003). Zinc nutrition of wheat: II: Interaction of zinc with other trace elements. Asian J. Plant Sci., 2(2): 156-160.

Inoue, M., I. Ebashi, N. Watanabe and Y. Morino (1989). Synthesis of a superoxide dismutase derivative that circulates bound to albumin and accumulates in tissues whose pH is decreased. Biochem., 28(16): 6619-6624.

Jackson, T. L., J. Hay and D. P. Moore (1967). The effect of Zn on yield and chemical composition of sweet corn in Willamette Valley. Am. Soc. Hort. Sci. 91: 462-471.

Jacobsen, J., G. Jackson and C. Jones (2003). Fertilizer guidelines for Montana crops. Coop. Ext. Publ. EB, 161.

Jahiruddin, M., B. T. Chambers, N. T. Livesey and M. S. Cresser (1986). Effect of liming on extractable Zn, Cu, Fe and Mn in selected Scottish soils. J. Soil Sci., 37: 603-615.

Jauregui, M. A. and H. M. Reisenauer (1982). Calcium carbonate and manganese dioxide as regulators of available manganese and iron. Soil Sci., 134(2): 105-110.

Johansen, C. and K. L. Sahrawat (1991). Strategies for maximizing the efficiency of phosphorus utilization in cropping systems involving chickpea and pigeonpea. In *Phosphorus Nutrition of Grain Legumes in the Semi-Arid Tropics.* Eds C. Johansen, K. K. Lee and K. L. Sahrawat. International Crops Research Institute for the Semi-Arid Tropics. Patancheru, Andhra Pradesh, India. pp. 227-241.

Jones Jr, J. B., B. Wolf and H. A. Mills, H. A. (1991). *Plant Analysis Handbook. A Practical Sampling, Preparation, Analysis, and Interpretation Guide.* Micro-Macro Publishing, Athens, pp. 195-203.

Jordan, W. R., W. A. Dugas Jr and P. J. Shouse (1983). Strategies for crop improvement for drought-prone regions. Agr. Water Manage., 7(1): 281-299.

Jungk, A. O., Y. Waisel, A. Eshel and U. Kafkafi (2002). Dynamics of nutrient movement at the soil-root interface. Plant roots: The hidden half, (Ed. 3), 587-616.

Jyung, W.H., A. Ehmann, K. K. Schlender and J. Scala (1975). Zinc nutrition and starch metabolism in *Phaseolus vulgaris* L. Plant Physiol., **55**: 414-420.

Kabata-Pendias, A. (2010). *Trace Elements in Soils and Plants*. Boca Raton, FL: CRC press.

Kastrup, V., S. Steiger, U. Luttge and E. L. K. E. Fischer-Schliebs (1996). Regulatory effects of zinc on corn root plasma membrane H^+-ATPase. New phytol., 134(1): 61-73.

Katyal, J. C. and N. S. Randhawa (1983). Micronutrients (FAO Fertilizer and Plant Nutrition Bulletin 7). *FAO, Rome, Italy*.

Kausar, M.A., F. M. Chaudhry, A. Rashid, A. Latif and S. M. Alam (1976). Micronutrient availability to cereals from calcareous soils. I. Competitive zinc and copper deficiency and their mutual interaction in rice and wheat. Plant Soil, 45: 397-410.

Kaya, C., D. Higgs and A. Burton (1999). Foliar application of iron as a remedy for zinc toxic tomato plants. J. Plant Nutr., 22(12): 1829-1837.

Kessler, B. (1961). Ribonucleases as a guide for the determination of zinc deficiency in orchard trees. In 'Plant analysis and fertilizer problems'. (Ed. W Reuther) pp. 314-322. (Am. Inst. Biol. Sci.: Washington, USA)

Kessler, B. and S. P. Monselise (1959). Studies on ribonuclease, ribonucleic acid and protein synthesis in healthy and rice–deficient citrus leaves. Physiol. Plant., 12: 1-7.

Khorgamy, A., A. Farnia, J. S. Tenywa, G. D. Joubert, D. Marais, P. R. Rubaihayo and M. P. Nampala (2009). Effect of phosphorus and zinc fertilisation on yield and yield components of chick pea cultivars. In *9th African Crop Science, Conference Proceedings, Cape Town, South Africa, 28 September-2 October 2009.* (pp. 205-208). African Crop Science Society.

Kim, T. and H. Y. Wetzstein (2003). Cytological and ultrastructural evaluations of zinc deficiency in leaves. J. Am. Soc. Hortic. Sci., 128(2): 171-175.

Klewicki, J. K. and J. J. Morgan (1998). Kinetic behavior of Mn (III) complexes of pyrophosphate, EDTA, and citrate. Environ. Sci. Tech., 32(19): 2916-2922.

Klewicki, J. K. and J. J. Morgan (1999). Dissolution of β-MnOOH particles by ligands: pyrophosphate, ethylenediaminetetraacetate, and citrate. Geochimica et cosmochimica acta, 63(19), 3017-3024.

Kochian, L. V. (1993). Zinc absorption from hydroponic solutions by plant roots. In *Zinc in soils and plants* (pp. 45-57). Springer Netherlands.

Krauskopf, K. B. (1972). Geochemistry of micronutrients. In *Micronutrients in agriculture*. J. J. Mortvedt, P. M. Giordano and W. L. Lindasy, Eds., Soil Sci. Soc. Am., Madison, Wisconsin.

Krishnamurti, G. S. R. and P. M. Huang (1992). Dynamics of potassium chloride induced manganese release in different soil orders. Soil Sci. Soc. Am. J., 56(4): 1115-1123.

Krishnamurti, G. S. R., P. M. Huang, L. M. Kozak, H. P. W. Rostad and K. V. Rees (1997). Distribution of cadmium in selected soil profiles of Saskatchewan, Canada: Speciation and availability. Can. J. Soil Sci., 77(4): 613-619.

Kuldeep, S. (2009). The critical zinc deficiency levels in Indian soils and cereal crops. In *The Proceedings of the International Plant Nutrition Colloquium XVI*.

Kubota, J. and W. H. Allaway (1972). Geographic distribution of trace element problems. In *Micronutrients in agriculture*. J. J. Mortvedt, P. M. Giordano and W. L. Lindsay, Eds, pp. 525-554. Soil Sci. Soc. Am. Wisconsin, Madison.

Kuperman, R. G. and M. M. Carreiro (1997). Soil heavy metal concentrations, microbial biomass and enzyme activities in a contaminated grassland ecosystem. Soil Biol. Biochem., 29(2): 179-190.

Langin, E. J., R. C. Ward, R. A. Olson and H. F. Rhoades (1962). Factors responsible for poor response of corn and grain sorghum to phosphorus fertilization: II. Lime and P placement effects on P-Zn relations. Soil Sci. Soc. Am. J., 26(6): 574-578.

Lauer, M. J. and D. G. Blevins (1989). Dry matter accumulation and phosphate distribution in soybean grown on varying levels of phosphate nutrition 1. J. Plant Nutr., 12(9): 1045-1060.

Leach, W. and C. D. Taper (1954). Studies in plant mineral nutrition: II. the absorption of iron and manganese by dwarf kidney bean, tomato, and onion from culture solutions. Can. J. Bot., 32(5): 561-570.

Lee, C. R., G. R. Craddock and H. E. Hammar (1969). Factors affecting plant growth in high-zinc medium: I. Influence of iron on growth of flax at various zinc levels. Agron. J., 61(4): 562-565.

Leece, D. R. (1978). Distribution of physiologically inactive zinc in maize growing on a black earth soil. Crop Pasture Sci., 29(4): 749-758.

Leidi, E. O., M. Gomez and M. D. De La Guardia (1987). Soybean genetic differences in response to Fe and Mn: activity of metalloenzymes. In *Genetic Aspects of Plant Mineral Nutrition* (pp. 463-470). Springer Netherlands.

Lewis, D. C. (1992). Effect of plant age on the critical inorganic and total phosphorus concentrations in selected tissues of subterranean clover (*cv. Trikkala*). Crop Pasture Sci., 43(1): 215-223.

Li, H. Y., Y. G. Zhu, S. E. Smith and F. A. Smith (2003). Phosphorus–zinc interactions in two barley cultivars differing in phosphorus and zinc efficiencies. J. Plant Nutr., 26(5): 1085-1099.

Liao, H., G. Rubio, X. Yan, A. Cao, K. M. Brown and J. P. Lynch (2001). Effect of phosphorus availability on basal root shallowness in common bean. Plant Soil, 232(1-2): 69-79.

Lide, D. R. (Ed.). (2004). *CRC Handbook of Chemistry and Physics*. CRC press.

Liew, Y. A., S. S. Omar, M. H. A. Husni, M. Z. Abidin and N. A. P. Abdullah (2010). Effects of micronutrient fertilizers on the production of MR 219 rice (*Oryza sativa* L.). Malay. J. S. Sci., 14: 71-82.

Lin, H. S., K. J. McInnes, L. P. Wilding and C. T. Hallmark (1997). Low tension water flow in structured soils. Can. J. Soil Sci., 77(4): 649-654.

Lindsay, W. L. (1972). Inorganic phase equilibria of micronutrients in soils. In *Micronutrients in agriculture*, Eds J. J. Mortvedt, P. M. Giordano and W. L. Lindsay, pp. 41-57. Wisconsin, Madison, USA.

Lindsey, K. E. (1973). Phosphate-induced zinc deficiency in seed production in *Medicago sativa* L (Doctoral dissertation, Texas A and M University.).

Lindsay, W. L. (1979). *Chemical Equilibria in Soils*. John Wiley and Sons Ltd..

Lindsay, W. L. (1991). Inorganic equilibria affecting micronutrients in soils. In *Micronutrients in agriculture*, Eds J. J. Mortvedt, P. M. Giordano and W. L. Lindsay, pp. 89-112. Wisconsin, Madison, USA.

Lombnæs, P. and B. R. Singh (2003). Effect of free manganese activity on yield and uptake of micronutrient cations by barley and oat grown in chelator-buffered nutrient solution. Acta Agric. Scand. (B), 53(4): 161-167.

Loneragan, J. F. (1951). The effect of applied phosphate on the uptake of zinc by flax. Aust. J. Biol. Sci., 4(2): 108-114.

Loneragan, J. F. (1975). The availability and absorption of trace elements in soil-plant systems and their relation to movement and concentrations of trace elements in plants. In '*Trace Elements in Soil-Plant-Animal Systems*'. (Eds. DJD Nicholas, AR Egan) pp. 109-134. (Acad. Press: New York, USA)

Loneragan, J. F. and M. J. Webb (1993). Interactions between zinc and other nutrients affecting the growth of plants. Develop. Plant Soil Sci., 55: 119-119.

Loneragan, J. F., D. L. Grunes, R. M. Welch, E. A. Aduayi, A. Tengah, V. A. Lazar and E. E. Cary (1982). Phosphorus accumulation and toxicity in leaves in relation to zinc supply. Soil Sci. Soc. Am. J., 46(2): 345-352.

Loneragan, J. F., T. S. Grove, A. D. Robson and K. Snowball (1979). Phosphorus toxicity as a factor in zinc-phosphorus interactions in plants. Soil Sci. Soc. Am. J., 43(5): 966-972.

Longnecker, N. E. and A. D. Robson (1993). Distribution and transport of zinc in plants. In '*Zinc in Soils and Plants*'. (Ed. AD Robson) pp. 79-91. (Kluwer Acad. Publ.: Dordrecht, The Netherlands)

López-Millán, A. F., D. R. Ellis and M. A. Grusak (2005). Effect of zinc and manganese supply on the activities of superoxide dismutase and carbonic anhydrase in *Medicago truncatula* wild type and *raz* mutant plants. Plant sci., 168(4): 1015-1022.

Lu, Z., H. S. Grewal and R. D. Graham (1998). Dry matter production and uptake of zinc and phosphorus in two oilseed rape genotypes under differential rates of zinc and phosphorus supply. J. Plant Nutr., 21(1): 25-38.

Lucas, R. E. and J. F. Davis (1961). Relationship between pH values of organic soils and availability of twelve plant nutrients. Soil Sci., 92: 177-182.

Lynch, J. (1995). Root architecture and plant productivity. Plant Physiol., 109(1): 7.

Lynch, J. P. and K. M. Brown (2001). Topsoil foraging–an architectural adaptation of plants to low phosphorus availability. Plant Soil, 237(2): 225-237.

Mackay, A. D. and J. K. Syers (1986). Effect of phosphate, calcium, and pH on the dissolution of a phosphate rock in soil. Fert. Res., 10(2): 175-184.

Malamy, J. E. (2005). Intrinsic and environmental response pathways that regulate root system architecture. Plant Cell Environ., 28(1): 67-77.

Malavolta, E. and A. M. L. Neptune (1977). Studies on the placement of fertilizer phosphorus in tropical crops. *Phosphorus in agriculture*, 70: 93-97.

Mandal, B. and L. N. Mandal (1990). Effect of phosphorus application on transformation of zinc fraction in soil and on the zinc nutrition of lowland rice. Plant Soil, 121(1): 115-123.

Marsh, K. B., L. A. Peterson and B. H. McCown (1989). A microculture method for assessing nutrient uptake II. The effect of temperature on manganese uptake and toxicity in potato shoots. J. Plant Nutr., 12(2): 219-232.

Marschner, H. (1983). General introduction to the mineral nutrition of plants. In *Inorganic plant nutrition* (pp. 5-60). Springer Berlin Heidelberg.

Marschner, H. (2002). Mineral nutrition of higher plants, 2nd ed. San Diego, CA: Academic Press.

Marschner, H. (2012). *Marschner's mineral nutrition of higher plants* (Vol. 89). P. Marschner (Ed.). Academic press.

Marschner, H. and G. M. Rimmington (1996). Mineral nutrition of higher plants. Academic Press, London.

Marschner, H. and I. Cakmak (1989). High light intensity enhances chlorosis and necrosis in leaves of zinc, potassium, and magnesium deficient bean (*Phaseolus vulgaris*) plants. J. Plant Physiol., 134(3): 308-315.

Marschner, H. and V. Römheld (1994). Strategies of plants for acquisition of iron. Plant Soil, 165(2): 261-274.

Marschner, H., E. A. Kirkby and I. Cakmak (1996). Effect of mineral nutritional status on shoot-root partitioning of photoassimilates and cycling of mineral nutrients. J. Exp. Bot., 47(Special Issue): 1255-1263.

Marsh, K. B. and L. A. Peterson (1990). Gradients in Mn accumulation and changes in plant form for potato plants affected by Mn toxicity. Plant Soil, 121(2): 157-163.

Masayuki, T., I. Nakagawa, H. Kazuhiro, I. Takehiro, O. Koichi and F. Michihiro (1989). Production of superoxide dismutase from *Streptococcus lactis* using a bioreactor with a microfiltration module. Agric. Bioi. Chem., 53(9): 2447-2453.

Masoni, A., L. Ercoli, M. Mariotti and I. Arduini (2007). Post-anthesis accumulation and remobilization of dry matter, nitrogen and phosphorus in durum wheat as affected by soil type. Eur. J. Agron., 26(3): 179-186.

Massonneau, A., E. Martinoia, K. J. Dietz and T. Mimura (2000). Phosphate uptake across the tonoplast of intact vacuoles isolated from suspension-cultured cells of Catharanthus roseus (L.) G. Don. Planta, 211(3), 390-395.

Mawardi, A. H., A. Serry, S. G. Awad and R. M. Kamal (1975). Wheat and corn production on calcareous soils as affected by P and Zn application. Egypt. J. Soil. Sci. Spec. Issue, 361-365.

May, G. M. and M. P. Pritts (1993). Phosphorus, zinc, and boron influence yield components in ‘earliglow' strawberry. J. Am. Soc. Hort. Sci., 118(1): 43-49.

McCully, M. (1995). How Do Real Roots Work?(Some New Views of Root Structure). Plant Physiol., 109(1): 1.

McHargue, J. S. (1922). The role of manganese in plants1. J. Am. Chem. Soc., 44(7): 1592-1598.

McKenzie, R. M. (1989). Manganese oxides and hydroxides. *Minerals in soil environments*, (mineralsinsoile), 439-465.

McLaughlin, M. J., D. Reuter and G. Rayment (1999). Soil testing-principles and concepts. In *Soil Analaysis and Interpretation Manual*. Eds, K. I. Peverill, L. A. Sparrow and D. J. Reuter, CSIRO, Collingwood, pp 1-21.

McMall, P.J. and D. Bouma (1973). Zinc deficiency, carbonic anhydrase and photosynthesis in leaves of spinach. Plant Physiol., 52: 229-232.

Melsted, S.W., H. L. Motto and T. R. Peck (1969). Critical plant nutrient composition values useful in interpreting plant analysis data. Agron. J., 61: 17-20.

Memon, A. R. and M. Yatazawa (1982). Chemical nature of manganese in the leaves of manganese accumulator plants. Soil Sci. Plant Nutr., 28(3): 401-412.

Mengel, K., H. Kosegarten, E. A. Kirkby and T. Appel (Eds.). (2001). *Principles of plant nutrition*. Int. Potash Inst., Bern, Switzerland.

Millikan, C. R. (1951). Diseases of flax and linseed. Technical Bulletin 9, Department of Agriculture Victoria, Australia, pp. 140.

Millikan, C. R. (1963). Effects of different levels of zinc and phosphorus on the growth of subterranean clover (*Trifolium subterraneum* L.). Crop Pasture Sci., 14(2): 180-205.

Millikan, C. R., B. C. Hanger and E. N. Bjarnason (1968). Effect of phosphorus and zinc levels in the substrate on ^{65}Zn distribution in subterranean clover and flax. Aust. J. Biol. Sci., 21(4): 619-640.

Mimura, T., K. Sakano and T. Shimmen (1996). Studies on the distribution, re-translocation and homeostasis of inorganic phosphate in barley leaves. Plant Cell Environ., 19(3): 311-320.

Miyao, M. and Y. Inoue (1991). Enhancement by chloride ions of photoactivation of oxygen evolution in manganese-depleted photosystem II membranes. Biochem., 30(22): 5379-5387.

Moraghan, J. T. (1985). Manganese nutrition of flax as affected by FeEDDHA and soil air drying. Soil Sci. Soc. Am. J., 49(3): 668-671.

Mortensen, J. J. (1963). Complexing of metals by soil organic matter. Soil Sci. Soc. Am. Proc., 27: 179-186.

Mortvedt, J. J. (1991). Function of micronutrients in plants. Micronutrients in Agriculture. pp. 297-328.

Mortvedt, J. J. and J. J. Kelsoe (1988). Grain sorghum response to banded acid-type fertilizers in iron deficient soil. J. Plant Nutr., 11: 1297-1310.

Moussa, B. I. M., M. S. A. Dahdoh and H. M. Shehata (1996). Interaction effect of some micronutrients on yield, elemental composition and oil content of peanut. Commun. Soil Sci. Plant Anal., 27(5-8): 1995-2004.

Nacry, P., G. Canivenc, B. Muller, A. Azmi, H. Van Onckelen, M. Rossignol and P. Doumas (2005). A role for auxin redistribution in the responses of the root system architecture to phosphate starvation in Arabidopsis. Plant Physiol., 138(4), 2061-2074.

Nair, K. P. P. and G. Probhat (1977). Differential response of tropical maize genotypes to zinc and manganese nutrition. Plant Soil, 47: 149-159.

Nambiar, K. K. M. and D. P. Motiramani (1981). Tissue Fe/Zn ratio as a diagnostic tool for prediction of Zn deficiency in crop plants. Plant Soil, 60(3): 357-367.

Nandi, S. K., R. C. Pant and P. Nissen (1987). Multiphasic uptake of phosphate by corn roots. Plant Cell Environ., 10(6), 463-474.

Natr, L. (1992). Mineral nutrients-a ubiquitous stress factor for photosynthesis (Review). *Photosynthetica (Czech Republic)*.

Nicholas, D. J. D. (1975). The functions of trace elements in plants. In ‘Trace Elements in Soil-Plant-Animal Systems’. (Eds. DJD Nicholas, AR Egan) pp. 181-198. (Acad. Press: New York, USA)

Norvell, W. A. and R. M. Welch (1993). Growth and nutrient uptake by barley (*Hordeum vulgare* L. cv. Herta): Studies using an N-(2-hydroxyethyl) ethylenedinitrilotriacetic acid buffer nutrient solution technique I. Zinc ion requirement. Plant Physiol., 101: 619-625.

Norvell, W. A. and W. L. Lindsay (1972). Reactions of DTPA chelates of iron, zinc, copper, and manganese with soils. Soil Sci. Soc. Am. J., 36(5): 778-783.

Obata, H. and M. Umebayashi (1988). Effect of zinc deficiency in protein synthesis in cultured tobacco plant cells. Soil Sci. Plant Nutr., 34: 351-357.

Obata, H., S. Kawamura, K. Senoo and A. Tanaka (1999). Changes in the level of protein and activity of Cu/Zn-superoxide dismutase in zinc deficient rice plant, *Oryza sativa* L. Soil Sci. Plant Nutr., 45(4): 891-896.

Ohki, K. (1978). Zinc concentration in soybean as related to growth, photosynthesis, and carbonic anhydrase activity. Crop Sci., 18(1): 79-82.

Okabe, K., S. Y. Yang, M. Tsuzuki and S. Miyachi (1984). Carbonic anhydrase: its content in spinach leaves and its taxonomic diversity studied with anti-spinach leaf carbonic anhydrase antibody. Plant sci. letters, 33(2): 145-153.

Olsen, S. R. (1972). Micronutrient interactions. In *Micronutrients in Agriculture*, Eds. J. J. Mortvedt, P. M. Giordano and W. L. Lindsay, pp. 243-264. Soil. Sci. Soc. Am., Wisconsin, Madison, USA.

Olsen, S. R. and A. D. Flowerday (1971). Fertilizer phosphorus interactions in alkaline soils. In *Fertilizer Technology and Use*. 2nd edition.

Oniani O. G., M. Chater, G. E. G. Mattingly (1973). Some effects of fertilizers and farmland manure on the organic phosphorus in soils. J. Soil Sci., 24: 1-9.

Orabi, A. A. and M. Abuleenane (1980). Zinc-phosphorus relationship in rice nutrition. Agric. Res. Rev., 58(5): 153-163.

Oseni, T. O. (2009). Growth and zinc uptake of sorghum and cowpea in response to phosphorus and zinc fertilization. World J. Agric. Sci., 5(6): 670-674.

O'Sullivan, M. (1970). Aldolase activity in plants as an indicator of zinc deficiency. J. Sci. Fd. Agric., 21: 607-609.

Ozanne, P.G., T. C. Shaw and D. C. Kirton (1965). Pasture responses to traces of zinc in phosphate fertilizers. Aust. J. Exp. Agric. Anim. Husb., 5: 29-33.

Pandey, N. and C. P. Sharma (1989). Zinc deficiency effect on photosynthesis and transpiration in sunflower and its reversal on making up the deficiency. Indian J. Exp. Biol., 27(4): 376-377.

Papakosta, D. K. (1994). Phosphorus accumulation and translocation in wheat as affected by cultivar and nitrogen fertilization. J. Agron. Crop Sci., 173(3-4): 260-270.

Parker, D. R., J. J. Aguilera and D. N. Thomason (1992). Zinc-phosphorus interactions in two cultivars of tomato (*Lycopersicon esculentum* L.) grown in chelator-buffered nutrient solutions. Plant Soil, 143(2): 163-177.

Patrick, J. W. H. and R. E. Henderson (1981). Reduction and re-oxidation cycles of manganese and iron in flooded soil and in water solution. Soil Sci. Soc. Am. J., 45: 855-859.

Pearson, J. N. and Z. Rengel (1994). Distribution and remobilization of Zn and Mn during grain development in wheat. J. Exp. Bot., 45(12): 1829-1835.

Peaslee, D. E. and C. R. Frink (1969). Influence of Silicie Acid on Uptake of Mn, Al, Zn, and Cu by Tomatoes (*Lycopersicum esculentum*) Grown on an Acid Soil. Soil Sci. Soc. Am. J., 33(4): 569-571.

Peverill, K. I., L. A. Sparrow and D. J. Reuter (1999). *Soil Analysis: An Interpretation Manual*. CSIRO publishing, Collingwood, Victoria, Australia.

Pinton, R., I. Cakmak and H. Marschner (1994). Zinc deficiency enhanced NADPH-dependent superoxider radical production in plasma membrane vesicles isolated from roots of bean plants. J. Exp. Bot., 45(1): 45-50.

© COPYRIGHT UPM

Piper, C.S. (1942). Investigations on copper deficiency in plants. J. Agric. Sci., 32: 143-178.

Pittman, J. K. (2005). Managing the manganese: molecular mechanisms of manganese transport and homeostasis. New Phytol., 167(3): 733-742.

Plaut, Z., F. C. Meinzer and E. Federman (2000). Leaf development, transpiration and ion uptake and distribution in sugarcane cultivars grown under salinity. Plant Soil, 218(1-2): 59-69.

Power, J. F. and R. Prasad (1997). *Soil Fertility Management for Sustainable Agriculture*. CRC press.

Prasad, K. G., U. C. Shukla and N. M. Safaya (1971). Effect of zinc application on phosphorus concentration and uptake in maize (*Zea mays* L.). Ind. J. Agric. Sci., 4: 1068-1073.

Preiss, J. (1984). Starch, sucrose biosynthesis and partition of carbon in plants are regulated by orthophosphate and triose-phosphates. Trends Biochem. Sci., 9(1): 24-27.

Price, C.A., H. E. Clark and E. A. Funkhouser (1972). Functions of micronutrients in plants. In ‘Micronutrients in Agriculture’. (Eds. JJ Mortvedt, PM Giordano, WL Lindsay) pp. 231-242. (Soil Sci. Soc. Am.: Wisconsin, USA).

Quartin, V. M., M. L. Antunes, M. C. Muralha, M. M. Sousa and M. A. Nunes (2001). Mineral imbalance due to manganese excess in triticales. J. Plant Nutr., 24(1): 175-189.

Raghothama, K. G. (1999). Phosphate acquisition. Annu. Rev. Plant Biol., 50(1), 665-693.

Raghothama, K. G. and A. S. Karthikeyan (2005). Phosphate acquisition. In *Root Physiology: from Gene to Function* (pp. 37-49). Springer Netherlands.

Randall, P. J. and D. Bouma (1973). Zinc deficiency, carbonic anhydrase, and photosynthesis in leaves of spinach. Plant Physiol., 52(3): 229-232.

Rashid, A., G. A. Couvillon and J. B. Jones (1990). Assessment of Fe status of peach rootstocks by techniques used to distinguish chlorotic and non-chlorotic leaves 1. J. Plant Nutr., 13(2): 285-307.

Rathmore, G. S., S. H. Wittwer, W. H. Jyung, Y. P. S. Rajaj and M. W. Adams (1970). Mechanism of zinc uptake in bean (*Phaseolus vulgaris*) tissues. Physiol. Plant., 23: 908-919.

Reddy, M. R. and H. F. Perkins (1976). Fixation of manganese by clay minerals. Soil Sci., 121(1): 21-24.

© UCC IPM

Reddy, M. R., A. Ronaghi and J. A. Bryant (1991). Differential responses of soybean genotypes to excess manganese in an acid soil. Plant Soil, 134(2): 221-226.

Reisenauer, H. M. (1988). Determination of plant-available soil manganese. In *Manganese in Soils and Plants* (pp. 87-98). Springer Netherlands.

Rengel, Z. (1995). Carbonic anhydrase activity in leaves of wheat genotypes differing in Zn efficiency. J. Plant Physiol., 147(2): 251-256.

Reuter, D. J. (1975). The recognition and correction of trace element deficiencies. In 'Trace Elements in Soil- Plant-Animal Systems'. (Eds. DJD Nicholas, AR Egan) pp. 291-324. (Acad. Press: New York, USA)

Reuter, D. J. (1980). Distribution of copper and zinc in subterranean clover in relation to deficiency diagnosis. Ph.D. thesis. (Murdoch Uni.: Murdoch, West. Aust.)

Reuter, D. J. and B. Robinson (1997). Plant analysis: An Interpretation Manual. CSIRO, Melbourne, Australia. pp. 572.

Reuter, D. J., D. G. Edwards and N. S. Wilhelm (1997). Temperate and tropical crops. Plant Anal.: an interpretation manual, 2: 81-284.

Reuter, D. J., J. F. Loneragan, A. D. Robson and D. Plaskett (1982). Zinc in subterranean clover (*Trifolium subterraneum* L. cv. Seaton Park). I. Effects of zinc supply on distribution of zinc and dry weight among plant parts. Aust. J. Agric. Res., 33: 989 -999.

Reynolds, E. S. (1963). The use of lead citrate at high pH as an electron-opaque stain in electron microscopy. J. Cell Biol., 17(1): 208-212.

Riceman, D. S. and G. B. Jones (1958). Distribution of zinc and copper in subterranean clover (*Trifolium subterraneum* L.) grown in culture solutions supplied with graduated amounts of zinc. Aust. J. Agric. Res., 9: 73-122.

Riley, I. T. (1994). Phosphorus nutrition of large-seeded chickpea cv. Macarena (Cicer arietinum) in the Ord River Irrigation Area, Western Australia. Anim. Prod. Sci., 34(6), 797-801.

Riley, M. M., J. W. Gartrell, R. F. Brennan, J. Hamblin and P. Coates (1992). Zinc deficiency in wheat and lupins in Western Australia is affected by the source of phosphate fertilizer. Aust. J. Exp. Agric., 32: 455-463.

Robinson, J. S. and J. K. Syers (1990). A critical evaluation of the factors influencing the dissolution of Gafsa phosphate rock. J. Soil Sci., 41(4): 597-605.

Robinson, J. S., J. K. Syers and N. S. Bolan (1992). Importance of proton supply and calcium-sink size in the dissolution of phosphate rock materials of different reactivity in soil. J. Soil Sci., 43(3): 447-459.

© COPYRIGHT UPM

Robson, A. D. and M. G. Pitman (1983). Interactions between nutrients in higher plants. In *Inorganic Plant Nutrition* (pp. 147-180). Springer Berlin Heidelberg.

Rodriguez, M. G., M. Gomez-Ortega and M. C. Alvarez-Tinaut (1981). Boron, copper, iron, manganese and zinc contents in leaves of flowering sunflower plants (*Helianthus annuus,* L.), grown with different boron supplies. Plant Soil, 62(3): 461-464.

Rose, T. J., J. Pariasca-Tanaka, M. T. Rose, Y. Fukuta and M. Wissuwa (2010). Genotypic variation in grain phosphorus concentration, and opportunities to improve P-use efficiency in rice. Field Crops Res., 119(1): 154-160.

Rosell, R. A. and A. Ulrich (1964). Critical zinc concentrations and leaf minerals of sugar beet plants. Soil Sci., 97(3): 152-167.

Rosen, J. A., C. S. Pike and M. L. Golden (1977). Zinc, iron, and chlorophyll metabolism in zinc-toxic corn. Plant Physiol., 59(6): 1085-1087.

Rupa, T. R., C. Srinivasa Rao, A. Subba Rao and M. Singh (2003). Effects of farmyard manure and phosphorus on zinc transformations and phyto-availability in two alfisols of India. Bioresource Tech., 87(3): 279-288.

Safaya, N. M. (1976). Phosphorus-zinc interaction in relation to absorption rates of phosphorus, zinc, copper, manganese, and iron in corn. Soil Sci. Soc. Am. J., 40(5): 719-722.

Sanchez-Raya, A. J., A. Leal, M. Gomez-Ortega and L. Recalde (1974). Effect of iron on the absorption and translocation of manganese. Plant Soil, 41(3): 429-434.

Sandmann, G. and P. Boger (1983). The enzymological function of heavy metals and their role in electron transfer processes of plants. *Encyclopedia of plant physiology*. *New series*. pp 563-596.

Sankhyan, N. K. and C. M. Sharma (1997), Effect of phosphorus and zinc fertilization on grain yield and uptake by maize (*Zea mays*). Ind. J. Agric. Sci., 67: 63-66.

Santa María, G. E. and D. H. Cogliatti (1988). Bidirectional Zn-fluxes and compartmentation in wheat seedling roots. J. Plant Physiology, 132(3): 312-315.

Sanyal, S. K. and S. K. De Datta (1991). Chemistry of phosphorus transformations in soil. In *Advances in Soil Science* (pp. 1-120). Springer New York.

SAS Institute Inc. 2010. *SAS/GRAPH* 9.2 *Reference, Second Edition*. Cary, NC: SAS Institute Inc.

Sasaki, H., T. Hirose, Y. Watanabe and R. Ohsugi (1998). Carbonic anhydrase activity and CO_2-transfer resistance in Zn-deficient rice leaves. Plant Physiol., 118(3): 929-934.

Sauchelli, V. (1969). *Trace Elements in Agriculture.* Van Nostrand Reinhold Co.

Schachtman, D. P., R. J. Reid and S. M. Ayling (1998). Phosphorus uptake by plants: from soil to cell. Plant Physiol., 116(2), 447-453.

Scherer, H. W. and W. Hofner (1980). Interactions of iron, manganese, and zinc during uptake and transport by maize and sunflower. Z. Pflanzenphysiologie, 97(1), 25-34.

Schmid, W. E., H. P. Haag and E. Epstein (1965). Absorption of zinc by excised barley roots. Physiol. Plant., 18(3): 860-869.

Schubert, T. S. (1992). *Manganese Toxicity of Plants in Florida*. Florida Department of Agriculture and Consumer Services, Division of Plant Industry.

Schwab, A. P. and W. L. Lindsay (1983). The effect of redox on the solubility and availability of manganese in a calcareous soil. Soil Sci. Soc. Am. J., 47(2): 217-220.

Schwartz, S. M., R. M. Welch, D. L. Grunes, E. E. Cary, W. A. Norvell, M. D. Gilbert, M. P. Meredith and C. A. Sanchirico (1987). Effect of zinc, phosphorus, and root-zone temperature on nutrient uptake by barley. Soil Sci. Soc. Am. J., 51 (2): 371-375.

Sharma, P. N., S. S. Bisht and N. Kumar (1994). Effect of zinc deficiency on chlorophyll content, photosynthesis and water relations of cauliflower plants. Photosynthetica 30: 353-359.

Sharma, R. N. (1983). Short note on response of maize (Ganga-5) to rates, time and method of zinc application. Indian J. Agron.

Shuman, L. M. (1977). Effect of soil properties on manganese adsorption isotherms for four soils. Soil Sci., 124(2): 77-81.

Shuman, L. M. (1988). Effect of phosphorus level on extractable micronutrients and their distribution among soil fractions. Soil Sci. Soc. Am. J., 52(1): 136-141.

Sillanpää, M. (1982). *Micronutrients and the Nutrient Status of Soils: A global Study* (No. 48). Food & Agriculture Org..

Siman, A., F. W. Cradock and A. W. Hudson (1974). The development of manganese toxicity in pasture legumes under extreme climatic conditions. Plant Soil, 41(1): 129-140.

Sims, J. T. (1986). Soil pH effects on the distribution and plant availability of manganese, copper, and zinc. Soil Sci. Soc. Am. J., 50(2): 367-373.

Singh, B., S. K. A. Natesan, B. K. Singh and K. Usha (2005). Improving zinc efficiency of cereals under zinc deficiency. Curr. Sci., 88(1): 36-44.

Singh, B. R. and K. Steenberg (1974). Plant response to micronutrients. Plant Soil, 40(3): 655-667.

Singh, J. P., R. E. Karamanos and J. W. B. Stewart (1986). Phosphorus-induced zinc deficiency in wheat on residual phosphorus plots. Agron. J., 78(4): 668-675.

Singh, J. P., R. E. Karamanos and J. W. B. Stewart (1988). The mechanism of phosphorus-induced zinc deficiency in bean (*Phaseolus vulgaris* L.). Can. J. soil sci., 68(2): 345-358.

Singh, M. V. (2008). Micronutrient deficiencies in crops and soils in India. In *Micronutrient deficiencies in global crop production* (pp. 93-125). Springer Netherlands.

Skoog, F. (1940). Relationship between zinc and auxin in the growth of higher plants. Am. J. Bot., 27: 939- 951.

Slansky, M. (1986). *Geology of Sedimentary Phosphate*. Academy Press, London, pp 210.

Slaton, N. A., C. E. Wilson, S. Ntamatungiro and R. J. Nornman (2001). Evaluation of zinc seed treatment for rice. Agron. J., 93: 152-157.

Sliman, Z. T. (1990). Effect of zinc on iron-stress-response mechanism of two soybean genotypes. J. King Saud Univ.

Smith, F. A., I. Jakobsen and S. E. Smith (2000). Spatial differences in acquisition of soil phosphate between two arbuscular mycorrhizal fungi in symbiosis with Medicago truncatula. New Phytol., 147(2): 357-366.

Smith, F. W. (1997). Interpretation of plant analysis: Concepts and principles. In *Plant Analysis: An Interpretation Manual*. Eds. D. J. Reuter and J. B. Robinson, pp 1-12. Inkata Press, Melbourne, Australia.

Smith, F. W. and J. F. Loneragan (1997). Interpretation of plant analysis: concepts and principles. In ‘Plant analysis: an interpretation manual’.(Eds DJ Reuter, JB Robinson) pp. 3–33.

Snir, I. (1983). Carbonic anhydrase activity as an indicator of zinc deficiency in pecan leaves. Plant Soil, 74(2): 287-289.

Snowball, K. and A. D. Robson (1986). *Symptoms of Nutrient Deficiencies: lupins*. Department of Soil Science and Plant Nutrition, Institute of Agriculture, University of Western Australia.

© COPYRIGHT UPM

Soloiman, D. and F. Y. H. Wu (1985). Preparation and characterisation of various *Eschrichia coli* RNA polymerases containing one or two intrinsic metal ions. Biochem., 24: 5079-5082.

Soltanpour, P. N. (1969). Effect of nitrogen, phosphorus and zinc placement on yield and composition of potatoes. Agron. J., 61(2): 288-289.

Spiller, S. and N. Terry (1974). Effects of zinc deficiency on the multiplication and expansion of sugarbeet leaf cells. Crop. Sci., 14: 293-295.

Srivastava, P. C. and U. C. Gupta (1996). *Trace Elements in Crop Production*. Science Publishers, INC.

Stanton, D. A. and R. D. T. Burger (1967). Availability to plants of zinc sorbed by soil and hydrous iron oxides. Geoderma, 1(1): 13-17.

Steenbjerg, F. (1951). Yield curves and chemical plant analysis. Plant Soil, 3: 97.

Stevenson, F. J. and M. A. Cole (1986). The phosphorus cycle. *Cycles of soil: carbon, nitrogen, phosphorus, sulfur, micronutrients. John Wiley and Sons, New York, NY*, 231-284.

Stukenholtz, D. D., R. J. Olsen, G. Gogan and R. A. Olson (1966). On the mechanism of phosphorus-zinc interaction in corn nutrition. Soil Sci. Soc. Am. J., 30(6): 759-763.

Suge, H., H. Takahashi, S. Arita and H. Takaki (1986). Gibberellin relationships in zinc deficient plants. Plant Cell Physiol., 27: 1010-1012.

Sutcliffe, J. F. and J. S. Pate (1977). *The Physiology of Garden Pea. Acad. Press*. A Subsidiary of Harcourt Brace Jovanovich PUb. 500 p.

Taiz, L. and E. Zaiger (1998). *Plant Physiology*. Second Edition. Sinauer Associates, Inc. USA.

Takkar, P. N. and N. S. Randhawa (1978). Micronutrients in Indian agriculture. Fert. News, 23(8): 3-26.

Terman, G. L., P. M. Giordano and S. E. Allen (1972). Relationships between dry matter yields and concentrations of Zn and P in young corn plants. Agron. J., 64(5), 684-687.

Terman, G. L., S. E. Allen and B. N. Bradford (1966). Response of corn to zinc as affected by nitrogen and phosphorus fertilizers. Soil Sci. Soc. Am. J., 30(1): 119-124.

Tiffin, L. O. (1967). Translocation of manganese, iron, cobalt, and zinc in tomato. Plant Physiol., 42(10): 1427-1432.

© COPYRIGHT UPM

Tiller, K. G. (1963). Weathering and soil formation on dolerite in Tasmania with particular reference to several trace elements. Aust. J. Soil Res., 1: 74-90.

Tiller, K. G. (1983). Micronutrients. In '*Soils: An Australian Viewpoint*'. pp. 365-387. CSIRO: Melbourne/Acad. Press: London.

Tinker, P. B. and P. H. Nye (2000). Solute movement in the rhizosphere.

Tisdale, S. L., W. L. Nelson and J. D. Beaton (1985). *Soil Fertility and Fertilizers*. Collier Macmillan Publishers.

Titus, B. D., B. A. Roberts and K. W. Deering (1998). Nutrient removals with harvesting and by deep percolation from white birch (*Betula papyrifera*) sites in central Newfoundland. Can. J. Soil S., 78(1): 127-137.

Traina, S. J. and H. E. Doner (1985). Copper-manganese (II) exchange on a chemically reduced birnessite. Soil Sci. Soc. Am. J., 49(2): 307-313.

Treeby, M., H. Marschner and V. Romheld (1989). Mobilization of iron and other micronutrients from a calcareous soil by plant–borne, microbial and synthetic metal chelators. Plant Soil, 114: 217-226.

Trostle, C. L., P. R. Bloom and D. L. Allan (2001). HEDTA–nitrilotriacetic acid chelator-buffered nutrient solution for zinc deficiency evaluation in rice. Soil Sci. Soc. Am. J., 65(2): 385-390.

Tsui, C. (1948). The role of zinc in auxin synthesis in the tomato plant. Am. J. Bot., 35: 172-179.

Tyner, E. H. (1946). The relation of corn yields to leaf nitrogen, phosphorus, and potassium content. Soil Sci. Soc. Am. Proc. 11, pp. 317-323.

Ulrich, A. (1952). Physiological bases for assessing the nutritional requirements of plants. Annu. Rev. Plant Physiol., 3: 207-228.

Ulrich, A. and F. G. Hills (1967). Principles and practices of plant analysis. In 'Soil Testing and Plant Analysis. Part II'. SSSA Special Publication Series 2, pp. 11-24. (Soil Sci. Soc. Am.: Madison, USA).

Ullrich-Eberius, C. I., A. Novacky and A. J. E. Van Bel (1984). Phosphate uptake in Lemna gibba G1: energetics and kinetics. Planta, 161(1): 46-52.

Ullrich, C. I. and A. J. Novacky (1990). Extra-and intracellular pH and membrane potential changes induced by K^+, Cl^-, $H_2PO_4^-$, and NO_3^- uptake and fusicoccin in root hairs of Limnobium stoloniferum. Plant Physiol., 94(4): 1561-1567.

Vallee, B. L. (1983). Zinc in biology and biochemistry. In 'Zinc Enzymes'. (Ed. TG Spiro) pp. 1-24. (John Wiley and Son: New York, USA).

Vallee, B. L., W. E. C. Wacker (1976). Metalloproteins and Metalloenzymes. In ‘CRC Handbook of Biochemistry and Molecular Biology Proteins’. (Ed. GD Fasman) pp. 276-292. (CRC: Boca Raton, USA).

Vance, C. P., C. Uhde-Stone and D. L. Allan (2003). Phosphorus acquisition and use: critical adaptations by plants for securing a nonrenewable resource. New Phytol., 157(3), 423-447.

Viets, F. G. (1962). Micronutrient availability, chemistry and availability of micronutrients in soils. J. Agric. Food Chem., 10(3): 174-178.

Viets, F. G. (1966). Zinc deficiency in the soil-plant system. *Zinc metabolism. Charles C. Thomas Publ., Springfield, IL*, 90-127.

Vlamis, J. and D. E. Williams (1973). Manganese toxicity and marginal chlorosis of lettuce. Plant Soil, 39(2): 245-251.

Wallace, A. and O. R. Lunt (1956). Reactions of some iron, zinc, and manganese chelates in various soils. Soil Sci. Soc. Am. J., 20(4): 479-482.

Warnock, R. E. (1970). Micronutrient uptake and mobility within corn plants (*Zea mays* L.) in relation to phosphorus-induced zinc deficiency. Soil Sci. Soc. Am. J., 34(5): 765-769.

Watanabe, H. and Y. Kobayashi (1986). X-Ray induced transport of inorganic elements in living rice leaves observed with X-ray fluorescence element mapping spectrometry. Agric. Biol. Chem., 50: 2077-2082.

Watanabe, F. S., W. L. Lindsay and S. R. Olsen (1965). Nutrient balance involving phosphorus, iron, and zinc. Soil Sci. Soc. Am. J., 29(5): 562-565.

Wear, J. I. (1956). Effect of soil pH and calcium on uptake of zinc by plants. Soil Sci., 81: 311- 315.

Webb, M. J. and J. F. Loneragan (1988). Effect of zinc deficiency on growth, phosphorus concentration, and phosphorus toxicity of wheat plants. Soil Sci. Soc. Am. J., 52(6): 1676-1680.

Webb, M. J., W. A. Norvell, R. M. Welch and R. D. Graham (1993). Using a chelate-buffered nutrient solution to establish the critical solution activity of Mn^{2+} required by barley (*Hordeum vulgare* L.). Plant Soil, 153(2): 195-205.

Welch, R. M. (1993). Zinc concentrations and forms in plants for humans and animals. In *Zinc in soils and plants* (pp. 183-195). Springer Netherlands.

Welch, R. M. and L. Shuman (1995). Micronutrient nutrition of plants. Crit. Rev. Plant Sci., 14(1): 49-82.

Welch, R. M. and W. A. Norvell (1993). Growth and nutrient uptake by barley (*Hordeum vulgare* L. *cv Herta*): studies using an N-(2-Hydroxyethyl) ethylenedinitrilotriacetic acid-buffered nutrient solution technique (II. Role of zinc in the uptake and root leakage of mineral nutrients). Plant Physiol., 101(2): 627-631.

Welch, R. M., W. H. Allaway, W. A. House, J. Kubota and R. J. Luxmoore (1991). Geographic distribution of trace element problems. *Micronutrients in agriculture*, Ed. 2: 31-57.

Wijebandara, D. I. (2007). Studies on distribution and transformation of soil zinc and response of rice to nutrients in traditional and system of rice intensification (Sri) methods of cultivation (Doctoral dissertation, University of Agricultural Sciences).

White, J. G. and R. J. Zasoski (1999). Mapping soil micronutrients. Field Crop Res., 60(1): 11-26.

White, M. C., A. M. Decker and R. L. Chaney (1979). Differential cultivar tolerance in soybean to phytotoxic levels of soil Zn. I. Range of cultivar response. Agron. J., 71(1): 121-126.

Wilbur, K. M. and N. G. Anderson (1948). Electrometric and colorimetric determination of carbonic anhydrase. J. Biol. Chem., 176(1): 147-154.

Wood, J. G. and P. M. Sibly (1952). Carbonic anhydrase activity in plants in relation to zinc content. Aust. J. Biol. Sci., 5(2): 244-255.

Yachandra, V. K., K. Sauer and M. P. Klein (1996). Manganese cluster in photosynthesis: where plants oxidize water to dioxygen. Chem. Rev., 96(7): 2927-2950.

Yoshiaki, I. and T. Ando (1968). Interaction between manganese and zinc in growth of rice plants. Soil Sci. Plant Nutr., 14(5): 201-206.

Young, R. D. (1969). Providing micronutrients in bulk-blended, granular fertilizers. Commer. Fert., 118: 21-24.

Youngdahl, L. J., L. V. Svec, W. C. Liebhardt and M. R. Teel (1977). Changes in the Zinc-65 distribution in corn root tissue with a phosphorus variable. Crop Sci., 17(1): 66-69.

Yu, Q. and Z. Rengel (1999). Micronutrient deficiency influences plant growth and activities of superoxide dismutases in narrow-leafed lupins. Ann. Bot., 83(2): 175-182.

Zhang, H., H. Yang, Y. Wang, Y. Gao and L. Zhang (2013). The response of ginseng grown on farmland to foliar-applied iron, zinc, manganese and copper. Ind. Crop Prod., 45: 388-394.

Zhang, T. Q. and A. F. MacKenzie (1997). Changes of phosphorous fractions under continuous corn production in a temperate clay soil. Plant Soil, 192(1): 133-139.

Zhang, Y. Q., Y. Deng, R. Y. Chen, Z. L. Cui, X. P. Chen, R. Yost and C. Q. Zou (2012). The reduction in zinc concentration of wheat grain upon increased phosphorus-fertilization and its mitigation by foliar zinc application. Plant Soil, 361(1-2): 143-152.

Zhao, Z. Q., Y. G. Zhu, F. A. Smith and S. E. Smith (2005). Cadmium uptake by winter wheat seedlings in response to interactions between phosphorus and zinc supply in soils. J. Plant Nutr., 28(9): 1569-1580.

Zuo, Y. and F. Zhang (2011). Soil and crop management strategies to prevent iron deficiency in crops. Plant Soil, 339(1-2): 83-95.

Zyrin, N. G., V. I. Rerikh and F. A. Tikhomirov (1976). Forms of zinc compounds in soils and its supply to plants. *Agrokhimiya (USSR)*.

© COPYRIGHT UPM