

!'"#\$%"&'()\*O-(. , %&57( 56\$ (. 3+4 +\$(2O.\*!/\$- , %&' ()\*' +\$ !"#

C+>D'B@!A- ; <!=%? 89: !.

<sup>4</sup>9/0; ; +< /50/ 5 <sup>3</sup>%&3450 6"7&8 .<sup>2</sup>/01+2, 0 )\* +, & .<sup>\*1</sup> !"# \$ %&! '(

89/10/19 :( )#\*+&#"\$" 88/8/20: !"#%&#"\$"

<0)=' , \$-5>"?+2"7450% , 89\$: "4; 2/3450% , -. /0 1 \$/0 -1

F#)G' 2"7450% , 89\$: "4; 2/3450% , B"C >-D. 2:)E , "\$?450% : %"A6 -3:2

<"H#I\$JK LDMO ?!)' 2"7450% , "\$%"A6 -4

Email: [rahimiloghman@yahoo.com](mailto:rahimiloghman@yahoo.com) :NG"30 0-PQ0 \*

#"\$" !

-@\*2 = \*2 0>? & 9#012 3 04 5-67 8! 9% & :-; /&\$+ -. ' # # () ) \* ! "# \$ % & , # \* + 14 ) # \$ % & ' ( # ! " -6GA07 ! 00 NH\$#&! " ! \*% M -LB! & ' 5BOK /B\$I -%\$. J DK C@E% & : "\$FG+ \$H / , D@ , =B! " C# 0; ! " ! \*AB! -@+ X\$P & : "\$FG+ \$H V W+ .-?"\*H ! " ! \*POH NRS\$H \$G1U? \*AB! -@+ -@\*2 = \*2 & N+! OH " ! \*% /\$Q, #\*+ & NPOH , K , #\*+ 14 c%\$; ! \$d@ 16 \$H NA"\$\ 2 J % \$K ^04 \_\$0 ! " ` ] A a0 ! : ! \$bH 5-67 : \$@7 \$H / , ?\$Z[7 ) # \$ % & ' Y# ! " =BOG+ f! Oh2 ! \$bi \$H (/OGK\$H =B-H B =gBOG@ " \*K =B-H) NF6% -Q\$; B (/OGK\$H =B-H B =gBOG@ " \*K \$H) J1e% -Q\$; f/OGK\$H \$Q(@?;\$@ , U#\$0% B /! \$%' , #9m2 n#\$G? .JA07 ! 00 NH\$#&! " ! \*% : \$@7 ( # C+\*2 Cu B Mn fZn f Fe k l . OH \$b?' Oj , D#! Mn ! -0% f: \$@7 , D#! B NR \*Q ) ZH Cu B Zn fFe Or \$6s ! -0% B J >[q OH /OGK\$H \$H N?& , # \$ % , K " " =D? J >[q OH /OGK\$H N?& , # \$ % Oj .J; " /! "N6u% Oj NR \*Q ) ZH , H , D#! & Cu B Zn fFe Or \$6s L\$0G? (@tdQ B : \$@7 - , #\*+ " " =D? n#\$G? .-D? ! "N6u% NR \*Q ) ZH , H , D#! & Mn L\$0G? B , D#! Mn J >[q fNR \*Q ) ZH Mn ! -0% B ! -0% B J >[q ) # 9A vs\$H -?"\*H ! " ! \*POH NRS\$H ! \*AB! -@+ -@\*2 = \*2 & / , D@ , =B! " C# 0; ! " , K /02OH /\$Q .-? : -; 5-67 : \$@7 NR \*Q ) ZH , H , D#! & 0\ 6s ( # L\$0G? (@tdQ B Fe

!\$7'-CAS f30\ % aK Or \$6s f5-67 f! \*AB! -@+ f' # # () ) \* ! "# \$ % & \* ) ( & \$ % ! "#

## Effects of Microbial Siderophores Produced by Native *Azotobacter chroococcum* Strains on Micronutrients Uptake by Wheat Plant

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### Abstract

In this study, 14 strains of *A. chroococcum* isolated from wheat grown fields around the city of Tabriz, in northwest of Iran, were assayed for siderophore production using chrome azurol-S agar (CAS-agar) method under in-vitro conditions. Results showed that some strains had relatively higher ability in siderophore production. In a pot culture experiment with sterile soil, wheat plants (*Triticum aestivum* L. CV. Falat) were inoculated with 14 bacterial strains. Positive control received nitrogen fertilizer without bacterial inoculation and negative control was left un-inoculated and without N- fertilizer. Totally, 16 treatments with four replications were arranged in completely randomized design. Concentrations and contents of Fe, Cu, Zn and Mn in shoot and root as well as translocations of these elements from root to the shoot were determined at the harvest time. Results showed that the inoculation with *Azotobacter* had significant effects on concentrations and contents of Fe, Zn and Cu in shoot and root. Translocations of Fe, Zn and Cu from root to the shoot were markedly increased in bacterial treatments compared to the positive and negative controls. Mn concentration and content as well as its translocation from root to the shoot were not significantly affected. In-vitro assessment of siderophore production revealed that the higher siderophore production in bacterial strains was in accordance with higher Fe in plant tissue and its translocation as well.

**Key words:** *Azotobacter chroococcum*, Siderophore, Wheat, Micronutrients, CAS-agar

(# "1dK & (*Triticum aestivum* L.) 5-67 ,[d.

NR lq 0\ 6s (#0Gdb% Fe (@tdQ .-?0HN% n?! Or \$6s

L\*\ E% -@\*2 !" ! / :-ds ) o? ,K J+ 30\ % aK

w#04 & -?\*2N% -6i 0Q 0\ 6s (# .-; \$HN% !" "

%&\$' &

,H Om6% X\$P /S\$H pH f= 0# /\$bK\$P 0GD@! !"

Cu B Zn fMn fFe Or \$6s N+0G+" J@H\$0 ) 0\$K

& =\$Q\$@7 \_[q NRS\$bK\$P (@i !" .""07N% =\$Q\$@7 / OH

!" NGI ,K J+ :-; :-Q\$D% "!" \*% NPOH !" \$H = \$Q\$@ N?& ,#\$% fN?gBOG@ /\$Q"\*K NASK O#" \$o% J+ :-; = \$Q\$@ \*d? B -; ! ) #9A \_ . \*% ) \* !"#\$\$%& =gBOG@ J@e2 c@' ,H -; ! ! " ) #9A ( # ,K ( # N-B \$# = \*% ! \*Q -@\*2 ce% /OGK\$H ` \$@r \* \ P O#\$+ \$# J+ %ZD% c%\$K ! \*xH & \*6Q f-6GUQ ^0x% ...B ! \*AB! -@+ ,u\$X% ( # -bi .(1991 = ! \$hdQ B B\$? &@ . ) J+ :-D? ,? ,#\$%& = \*6s ,H '# # ( ) ) \* !"#\$\$%& ,K : " " = \$D? O#\$+ ,h[H J+ Oj| % =gBOG@ J@e2 !" \$b62 B M\*%!) -; ! /\$Q= \*% ! \*Q -@\*2 c@0 & ` \$@r \* \ P \$? \$#!' ( @DKS) Ni ! \$0 - ' " \*% -@\*2 f(2000 = ! \$hdQ B (1996 = ! \$hdQ B \$m? \* + ) ! \*AB! -@+ -@\*2 f(1993 C+ \*2 ,K (2000 = ! \$hdQ B SB! \$?) ` \$FUA N7-66K cI c@' ,H .-6GUQ ab% 9@ -?0@7N% ` ! \*r /OGK\$H ( # /-6%" \* + c@' ,H ( @tdQ B ` ] hD% c@0 ( # " \* . B & \$@ " ! \*% (Q' ( @y2 ! " NHBOh@ /\$Q! \*AB! -@+ ! " \*P & \$@ " ! \*% (Q' \$@ " 5"0% OGd@ ,h6# B = \$Q\$@ & : "\$FG+ f-66KN% ( @y2 5-67 :\$@ & ,#I (2 w#04 & -N% -@ J@Q ! \*AB! -@+ -@\*2 ! " -6d? \*2 /\$Q, #\* + NPOH ,K -Q" N% = \$D? \$QN+ ! OH .(1384 N? \$@ -r ) -6K aK Or \$6s J>[q ) #9A \_1+ ) \* !"#\$\$%& /\$Q, #\* + N[r /\$Q! \$KB&\$+ N-B -? \*; N% :\$@ C+ \*2 30 \ % :-D? %ZD% c%\$K ! \*4 ,H & \*6Q ) #9A ( # ! " c@P" -@\*2 c@J? \$G} -? \*2N% = ' c#S" & Nh# .J+ fw@E2 ( # & 3-Q -; ; \$H /OGK\$H C+ \*2 ! \*AB! -@+ N\*%H , #\* + 14 ! \*AB! -@+ -@\*2 = \*2 NH\$#&! 5-67 8! 9% & :-; /&\$+ - . '# # ( ) ) \* !"#\$\$%& \$b?' Oj ( @u2 B / ,D@ =B! " ` ! \* \ H 9#012 3 04 ! " 5-67 :\$@ C+ \*2 30 \ % aK Or \$6s kI . ! " .-; \$HN% / ,? \$Z[7 ) # \$%&'

\$%+ #, # - . /

= \* @Uh[K & '# # ( ) ) \* !"#\$\$%& , #\* + 14 9#012 : \$pD? " X\$P /g\* < @ : \$pD# \$%&' NHBOh@ 9#012 3 04 5-67 8! 9% & \$Q, #\* + ( # .-? -; ; JAS#! " 0-30 wds & B ,s! 9% ) [GZ% /\$QJdUO & OF+B9#! 0@ X\$P B :\$@ ( # OF+B9#! /OGd@? \$+

! 00 :\$@ ! \$@P ! " (Q' /\$QJ@NK B NR\$@ , /\$Q"\*K /"#& Nx@E% JU#& ` ] hD% B ,6#9Q \$H N-B f"0@pH f= \$Q\$@ Fe ( @y2 / \$bQ ! & Op# " Nh# -; ; \$HN% : OdQ -@\*2 \$H ' '# # ( ) ) \* !"#\$\$%& /\$Q, #\* + & : "\$FG+ z\* A /\$b; B! ` ] hD% ,K -; ; \$HN% \_ + \$6% ! \*AB! -@+ /OGK\$H Y# '# # ( ) ) \* !"#\$\$%& . " ! -? L\$1? " ,H ! OH :B]s ,K J+ /& " &' 8\*? & =gBOG@ : -66KJ@e2 -? \*2N% \$QJ@\*H\$G% NPOH -@\*2 \$H f: \$@ =gBOG@ ( @y2 ( # ,[d. & . " \*; {0 B Oj| % :\$@ -; ; ! ) #9A ! " = " \*d? XOE% \$H ,K -6GUQ \$Q! \*AB! -@+ f\$QJ@\*H\$G% YdK :\$@ -; ; ! ,H f(Q' \$r \* \ Z% 30 \ % aK Or \$6s aK N<\*h<\*% = & B \$H N< N2\$1@K02 \$Q! \*AB! -@+ .-66KN% N1@K02 c@ \$H /\$Q-? \$p@ ,K -6GUQ (= \*G< " 500-2000) B NG@0- , + (Q' \$H -? \*@ / OH Nr \$ \ GP B -# -; ; B M07] @) -? ! " ` 9[A O#\$+ ,H J1U? /OGdK c# \$d2 8 \*? ( @ ! " \$Q! \*AB! -@+ : #B J@Q .(1999 = ! \$hdQ -? \*; N% " &' OF+B9#! ! " ,K NHBOh@ /\$QJ@\*H\$G% N2\$@ /\$Q-6# OA ! " (Q' /-@K ) o? c@' ,H \* + Y# & /\$Q ( @2B0) 966+ fc@B0[K 966+ fVf62 -6? \$% = \$Q\$@ B (... \$Q& -@JK O} B f&S2\$K f\$Q 5BOK\*( @+ ) 2aQ! (4 ( @JK" BOA = BOGh< cO\$? : "\$%) 3aQD@ /\$Q ( @2B0) /\$QN7\*#B ,H fOp# " / \* + & B (1995 06; ! \$%) J+ /! -0% \$H (Q' .-6KN% -@ " \$12! fX\$P ! " (Q' # \$P = B OA O \ 6s ( @! \$bi fOF+ \*G@ ! " -r ! " n6) "B-I \$H \$bK\$P OeK ! " N-B " \*; N% k\*UE% ( @& ,G+ \* ) ! " ,H \$r N#\$@0 \$2 Ne6P pH B , #\* b2 C# 0; ,H , . \*2 /\$QNUKB! -@ NUK ! \$GP\$+ ! " B NG@0- , + ch; ! " .(1987 & -6[ @ B ( # \*; ) " ! " " \* . B 5L\* [E%\$? J+ 9@ \$? ! \$@UH X\$P (Q' J>[q ,K Nx# 0; -@\*2 ! \*AB! -@+ C@E% C# 0; ,H \$+ \$) ! " = ! -? \$ . 9#! \_UK C@E% & ! " \*P & \$@ " ! \*% (Q' -6? \*GH \$2 -66KN% .-6# \$d?

1 Azotobacter chroococcum  
 2 Heame proteins  
 3 Non- heame proteins(Iron-sulfur proteins)  
 4 Ferredoxin  
 5 Insoluble oxyhydroxides

OH O>? "!" \*% !\$d@ wH\$x% NHBoh@ =\*@J?SW+ \*+ OG@  
 J#b? !" B -; ,A\$' :OFI :! \*#" B !IH OQ /B!  
 (@tdQ f-; :-?%; \*) X\$P NdK ! -o% \$H !IH /B!  
 -FI Jb. J@D} & NK&\$? ,#S \$H \$Q= -[7 X\$P , x+  
 .-; :-@%; \*) N7"\*<' & /O@7\*[. B X\$P JH\*4!  
 Oxo% k' \$H B (#&\*2 w#04 & ,?&B! \$Q= -[7 N%\$d2  
 \$QYQ\$@7 ,K N%\$p6Q -uh &B! -bi .-?;- /!\$@!' =BOG+  
 ,tQ\$@7 !\$bi ="OK Y62 w#04 & -?-%' =BO@H X\$P &  
 NAO\% " \*K ! -o% .-; ,G; 17 NOSH =-[7 OQ !" &  
 OFUA 75/6 mg kg<sup>-1</sup> c%; X\$P =\*%&' M\$+ OH &  
 a@+\$G} 27/2 mg kg<sup>-1</sup> fcW#02 ` \$FUA O)\*+ {16%  
 mg kg<sup>-1</sup> B \$Q= -[7 X\$P N%\$d2 ,H a@+\$G} ` \$F<\*+ {16%  
 -Q\$; !\$d@ ,H CoA :!B {16% & =gBOG@ 113/4 <sup>1</sup>  
 C+\*2 J; \$K & c10 Js\$+ 24) LB &B! =\$dQ !" J1e%  
 -; ,A\$' \$Q= -[7 X\$P ,H ( Oxo% k' OG@ N[ @ 365  
 C#0; !" \$Q= -[7 .( 1987 N. OP\*% B M \*U#\$H)  
 fJs\$+ 14 NR\$6; B! :!B" L\*4) -; ! Y0\$2 :-; LOG6K  
 28 2 &B! B 15 2 \_; L\*4 !" -; ! Y0\$2 /\$%"  
 8000 -10000) J6+!\*[A !\*? \$H B " 07NG?+\$ , , !"  
 NQ" ,[16+ ,[I 0% /\$bG? \$2 B -6GA07 ! 00 (VK\*  
 :\$% ,+ "B-I ,K -; ! :!B" =\$#\$) !" .-?;- /! -bp?  
 cK V% B /B! f96p6% f(Q' Or \$6s J>[q -@DK L\*4  
 .(1980,6@ \$K) -?;- /O@7 :&-? \$Q, D#! B N#\*Q ) ZH  
 B \$Q, D#! B N#\*Q ) ZH !" Or \$6s (# ! -o% (@tdQ  
 -#"07 ,1+\$E% 9@ N#\*Q ) ZH ,H ,D#! & \$b?' L\$og?  
 ,U#\$o% B \$QV?#\$# B ,#9m2 .(2009 = ! \$hdQ B M\*H\$7)  
 , x+ !" (h? " / ,6% " -bi =\*%&' +B! ,H \$Q (@p? \$@%  
 B SPSS ! 9A 50? & :"\$FG+ \$H -r !" 5 L\$dGI  
 \$H \$Q! "\*"d? a+! (@tdQ .-; 5\$m? MSTATC  
 .-@+! 5\$m? ,H Excel ! 9A 50?

:B] s f,?\*7 B V6. -@y2 / OH .-?"\*H :-; /&\$+ -.  
 Y@h2 & fNR\$@e, \*@H B Nh#g\* <\*A0% /\$b? \*%&' OH  
 : " & \*0A) -; :"\$FG+ 9@ 16S rRNA N<\*2 (@u2  
 Nh+ " 07\*6#B JDK C@E% !" \$Q/OGK\$H -GH .(1388  
 J+ -H O>? "!" \*% /\$QN6[K B O@h2 (2006 &6@hH)  
 =B! " C#0; !" ! \*AB! -@+ -@\*2 N#? \*2 VW+ .-?-%'  
 (!\$7' -CAS) M -LB! &' 5BOK +B! ,H B / ,D@,  
 .(1987 &-6[@ B (# \*; ) -; /O@7 :&-? \$Q, #\*+ (# !" <br>
 X\$P =\*"d? :"\$%' B / ,?Z[7 ) #\$\$\$&' 5\$m? Jb.  
 X\$P 507\*[@K 200 ! -o% 1387 :\$% ! \*#0b; !" \$Q= -[7  
 !" {0B) =\$; \*) Ju[P N2\$@e2 :\$pGU# ,s! 9% &  
 wds & 1 LB-. ` \$ \ ZD% \$H (9#012 Ob; z0; L\$d;  
 507\*[@K 2 \$H \$Q= -[7 VW+ .-; ,@b2 /OGd@? \$+ 0-30  
 B -?-"07 O} /OGd@? \$ 4 Y< & :-; : " " ! \*1s X\$P &  
 ,H fOFUd2 Y# ! \$DA f" 07 NG? \$+ , . ! "121) B] K\*2 !" <br>
 5-67 & N+! OH (# !" .-?;- =BOG+ (Js\$+ 2 `-%  
 :"\$FG+ (*T.aestivum* L. CV. Falat) ` ] A a0! :! \$bH  
 9#012 /&! B\$DK "\$b. ` \$@e2 9K0% & a0! (# ,K -;  
 :&-? aQ B 02 a\$+ f02 J; !" /\$Q! IH .-#"07 ,@b2  
 !" ) #\$\$\$&' (# .-?;- ! " ,? \* . B =BOG+ VW+ k\$ZG?  
 , #\*+ 14 c%; !\$d@ 16 \$H NA"\$ \ 2 J] \$K ^04 \_ \$0  
 fA-20 fA-10 fA-9 fA-5 fA-3 fA-2 fA-1) NR\$#OGK\$H  
 f(A-51 B A-48 fA-31 fA-29 fA-24 fA-23 fA-22  
 -Q\$; B (/OGK\$H =B-H B =gBOG@ " \*K \$H) J1e% -Q\$;  
 ! \$bi \$H (/OGK\$H =B-H B =gBOG@ " \*K =B-H) NF6%  
 12/58\$F2! B OGd@? \$+ 14/50x0 ,H N#\$Q= -[7 !" ! Oh2  
 /\$Q, #\*+ O@h2 B -; ! & V} .JA07 5\$m? OGd@? \$+  
 J@ud. fNh+ " 07\*6#B {#\$\$\$ JDK C@E% !" O>? "!" \*%  
 -I !" -6<! \$A Y% ! \$@u% M\$+ OH \$b?' NHBoh@%  
 .(1987 (%0; B \*6@i \*\$K) -; a@e62 <sup>1</sup>OD<sub>600nm</sub> = 0/7  
 OG@ N[ @ 365 C+\*2 J; \$K & c10 Js\$+ 24 \$Q = -[7  
 L\$h+}\$\*[@K 10 L "\$u% JH\*4! \$2 -?;- /!\$@!' Oxo% k'  
 :OFI 5 VW+ .(2005 5\$bK0@K) " \*; "\$m# (FC)  
 ! IH "-s Y# B "\$m# = -[7 OQ =B!" Yi \*K NEX+  
 -N[ @ 1 VW+ .JA07 ! 00 :OFI OQ cP " ! " ! ,? \*.

<sup>1</sup> Optical density

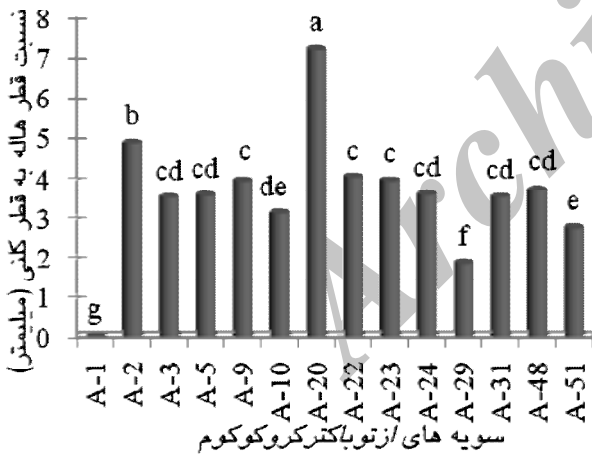
G\*?@ABC D1&-EF => \$%&'()\*+,-./:;<=>?@A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

| RS | D/A | 1 \$            | 1 !"l           | 2OM          | 3EC                    | pH <sup>3</sup> | 4CaCO <sub>3</sub> |
|----|-----|-----------------|-----------------|--------------|------------------------|-----------------|--------------------|
|    | (%) |                 |                 | (%)          | (dS m <sup>-1</sup> )  |                 | (%)                |
| 58 | 21  | 21              | 1 \$ >-T<br>UVS | 1/01         | 1/81                   | 8               | 11/52              |
|    |     | (1958 <-03X) -4 |                 | (1982 W?) -3 | (19969)0"A : <-005) -2 |                 | (2002 UE) -1       |

G\*?@ABC D1&-EF => \$%&'()\*+,-./:;<=>?@A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

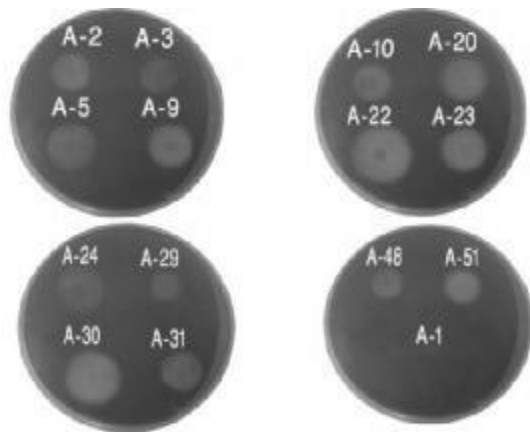
| 5N                     | 6P  | 7K  | 8Fe | 8Zn | 8Mn | 8Cu |
|------------------------|-----|-----|-----|-----|-----|-----|
| (mg kg <sup>-1</sup> ) |     |     |     |     |     |     |
| 300                    | 6/9 | 225 | 2/8 | 1/4 | 6/2 | 1/2 |

: RA/5) >-75-0K [ "A6 "l 8)E 2\$"\. ( : \$ -7 (1954 <6\$3YZ : ROI:6 ROI:6 ( : \$ -6 (1982U5-T-0 : )W)l) O6/DH; ( : \$ -5 (1978 O:\$-5: UA/W?) DTPA ( : \$ - 8 (1982 <-A)@+



32501

+ , 7" + #2) #2, MN\*, M  
 (#OGD# 2 B 20 / \$Q, #\* + , [r \$l n#\$G? M\$+ OH  
 = ' & -uH B "Oh? -@\*2 /! \*AB! -@+ Y# :! \$d; , #\* + B  
 -N% ! \*AB! -@+ : -66K -@\*2 (#OGdK 51 B 29 / \$Q, #\* +  
 .(2 B 1 ch; ) -6; \$H



\$#4 #2, M+, 7" + #2) G&T G&TV2U@2- ?Wl&X- -2 O54

. !"#"\$%&'()\*+,-./:;<=>?@A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

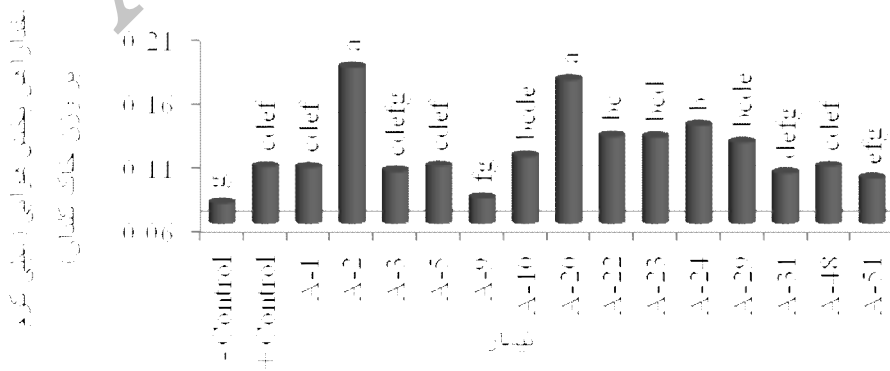
O1\*YI ; 9&JK + #X-

\_@02 , H 24 B 20 f2 / \$Q, #\* + 3 ch; M\$+ OH  
 -Q\$; ! \$d@ \$H , U#\$0% ! " -r ! " 78/8 B 125/7 f138/4  
 ! \$d@ \$H , U#\$0% ! " -r ! " 30 B 64/2 f73/4 B NF6%  
 ) #9A ! 5-67 : \$@7 N# \*Q ) ZH (Q' ! -0% J1e% -Q\$;

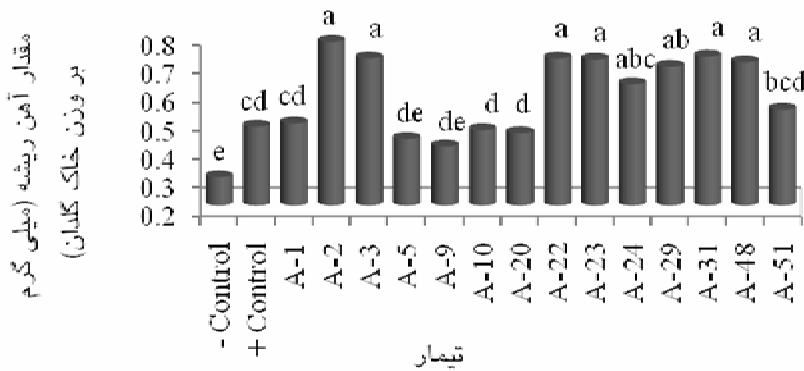
G&TOBP Q\*; R\* + # OS@&@?&T : + , 7" + #2) #2, MN\*, M -1 O54  
 .#4&O- + , 7" + #2) #2, M; U@& !"#"\$%&'()\*+,-./:;<=>?@A B C D E F G H I J K L M N O P Q R S T U V W X Y Z

O1\*YI ;9&K =HB1  
 Or \$6s J>[q "!"\*% !" \$Q(ϑ?;\$@ ,U#\$0% -?B!  
 .-; \$HN% Or \$6s ! -o% J@u' B \$H ,H\$D% \$T#0o2  
 O1\*,T DA< ?< ?Z1+ E\* [ - " G"+ \6JUJ- VTF !&X(@  
 (!&X(@ ] /&4)  
 \$Q,#\*+ 0#\$+ \$H ,U#\$0% !" 20 ,#\*+ 10 ch; w14  
 !" /! "N6u% 0j NF6% -Q\$; B J1e% -Q\$; /\$Q!\$@ B  
 ,H .J+ ,G; " N#\*Q ) ZH ,H ,D#! & (Q' L\$G?  
 B J1e% -Q\$; /\$Q!\$@ \$H ,U#\$0% !" ,#\*+ (# ,K/!\*4  
 (Q' ! -o% -r !" 37/2 B 56/7 @2 ,H NF6% -Q\$;  
 .J+ : " L\$G? N#\*Q ) ZH ,H \$Q,D#! & ! /OGD@  
 B 24 /\$Q,#\*+ !" N#\*Q ) ZH ,H ,D#! & /B! L\$G?  
 B NF6% -Q\$; !\$@ \$H ,U#\$0% !" /! "N6u% ) #9A 29  
 ! J1e% -Q\$; !\$@ B 23 ,#\*+ 9. ,H \$Q,#\*+ 0#\$+  
 !\$@ \$H ,U#\$0% !" \$Q,#\*+ (# .(11 ch; ) -Q"N% =\$D?  
 \$H ,U#\$0% !" B -r !" 22 B 23/8 @2 ,H J1e% -Q\$;  
 ! -o% -r !" 38/6 B 40/7 @2 ,H NF6% -Q\$; !\$@  
 .-?: " L\$G? N#\*Q ) ZH ,H ,D#! & ! /OGD@ /B!  
 N#\*Q ) ZH ,H ,D#! & V% L\$G? /\$Q(ϑ?;\$@ ,U#\$0%  
 -,#\*+ 9. ,H \$Q,#\*+ ,dQ ,K -Q"N% =\$D? 12 ch; !" &  
 V% L\$G? !" /! "N6u% ) #9A \_1+ 10B 5 f2 /\$Q  
 J1e% -Q\$; !\$@ \$H ,U#\$0% !" N#\*Q ) ZH ,H ,D#!  
 !" 10 ,#\*+ 9. ,H \$Q,#\*+ ,dQ (@tdQ .-? :-;  
 ,D#! & ! /OGD@ V% NF6% -Q\$; !\$@ \$H ,U#\$0%  
 .-?: " L\$G? N#\*Q ) ZH ,H 5-67

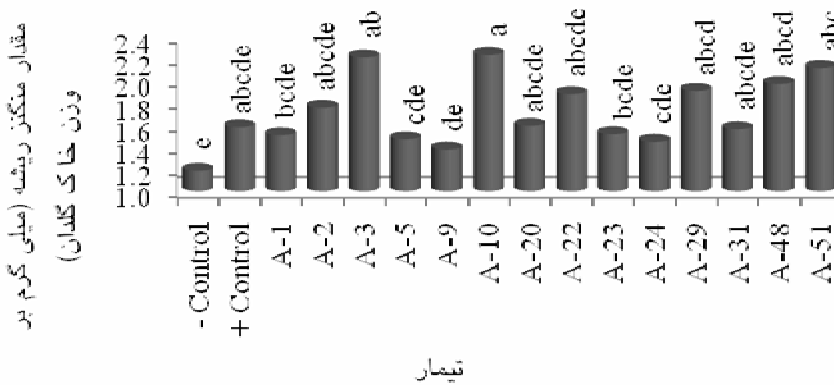
f3 f2 /\$Q,#\*+ ,K -Q"N% =\$D? 4 ch; n#\$G? .-?: " "  
 ,H J1e% -Q\$; !\$@ \$H ,U#\$0% !" 48 B 31 f29 f23 f22  
 47/5 f51/7 f46/1 f49/5 f50/2 f50/3 f62/6 @2  
 f140/3 f160 NF6% -Q\$; !\$@ \$H ,U#\$0% !" B -r !" )  
 #9A vs\$H -r !" 136 B 142/5 f130/5 f139 f140/2  
 !" \$Q,D#! 96p6% ! -o% .-?: :-; \$Q,D#! (Q' ! -o% !" -  
 -Q\$; !\$@ \$H ,U#\$0% !" 51 B 48 f29 f10 f3 /\$Q,#\*+  
 -r !" 79/1 B 66/8 f61/5 f89/2 f87/2 @2 ,H NF6%  
 /\$Q!\$@ \$H B Op#-h# \$H \$Q,#\*+ 0#\$+ (ϑ .JA\$# ) #9A  
 " ! -? " . B /! "N6u% ` B\$F2 NF6% -Q\$; B J1e% -Q\$;  
 B J1e% -Q\$; !\$@ ,K -Q"N% =\$D? 6 ch; .(5 ch; )  
 ,H NF6% -Q\$; !\$@ \$H ,U#\$0% !" 51 B 22 f2 /\$Q,#\*+  
 ) #9A vs\$H -r !" 47/1 B 47/7 f36/5 f50/8 @2 ,  
 U#\$0% .-?: :-; 5-67 :\$@7 N#\*Q ) ZH /B! ! -o%  
 -N% =\$D? 5-67 :\$@7 /\$Q,D#! /B! ! -o% /\$Q(ϑ?;\$@  
 !\$@ \$H ,U#\$0% !" 51 B 22 f20 f2 /\$Q,#\*+ ,K -Q"  
 -r !" 73/3 B 60/7 f71/7 f61/8 @2 ,H NF6% -Q\$;  
 ch; ) -?" " ) #9A ! 5-67 :\$@7 /\$Q,D#! /B! ! -o%  
 !" ! \$Q,D#! B N#\*Q ) ZH V% ! -o% 10 ,#\*+ .(7  
 -r !" 68/3 B 29 @2 ,H J1e% -Q\$; !\$@ \$H ,U#\$0%  
 61/3 B 72/5 @2 ,H NF6% -Q\$; \$H ,U#\$0% !" B  
 .(9 B 8 ch; ) J+ : " " ) #9A -r !" "



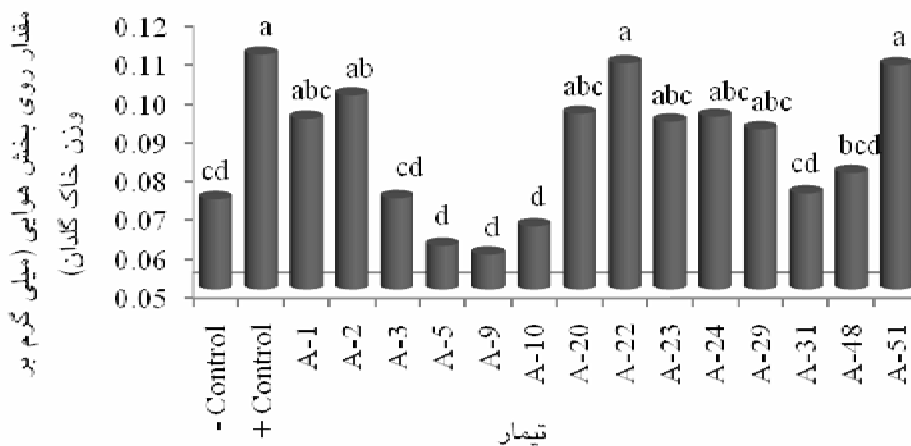
.a#JC O1\*,T DA<VTF +\*#X- ;<\$%&!()O\*\* B(A- G&T?1, ) ;2\_MG&TV2U@2- ?W1&X- -3 O54



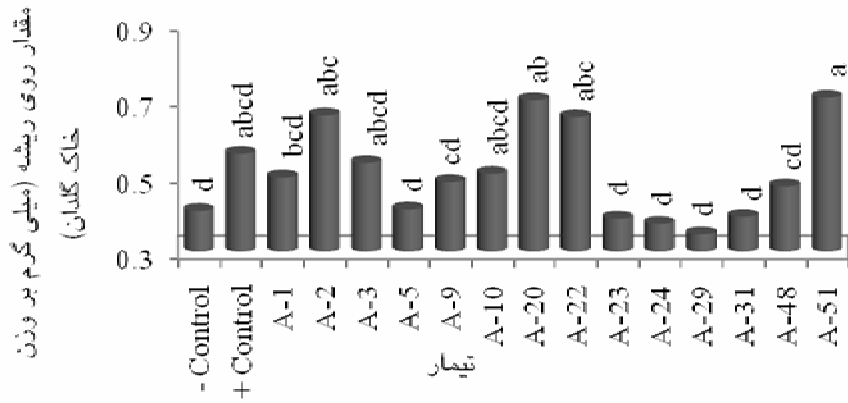
a.#JC ?Z1+ VTF +\*#X- ;<\$%&'()\*~ B(A- G&T?1, ) ;2^\_MG&TV2U@2- ?W1&X- -4 O54



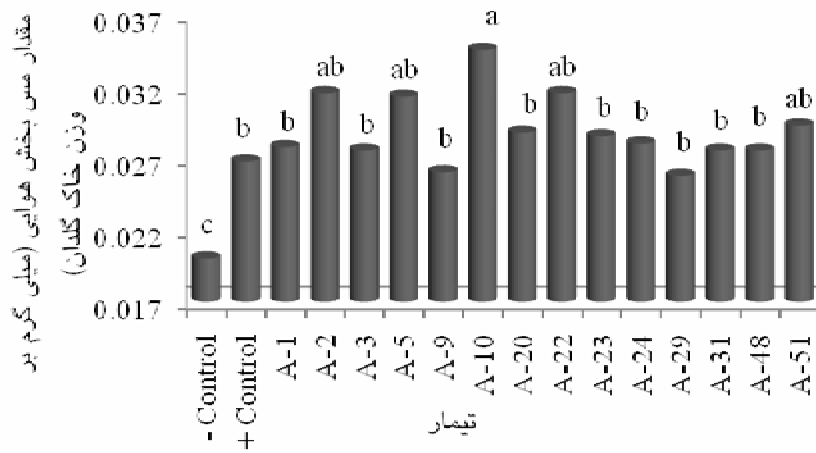
a.#JC ?Z1+ 6JU- +\*#X- ;<\$%&'()\*~ B(A- G&T?1, ) ;2^\_MG&TV2U@2- ?W1&X- -5 O54



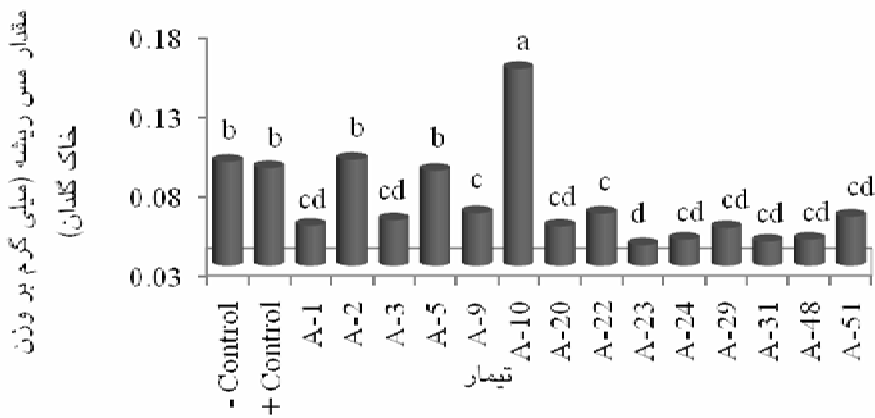
a.#JC O1\*, T DA<G"+ +\*#X- ;<\$%&'()\*~ B(A- G&T?1, ) ;2^\_MG&TV2U@2- ?W1&X- -6 O54



a.#JC ?Z1+ G"+ +\*#X- ;<\$%&'!( )^\* B(A- G&T?1, ) ;?\_MG&TV2U@2- ?W1&X- -7 O54

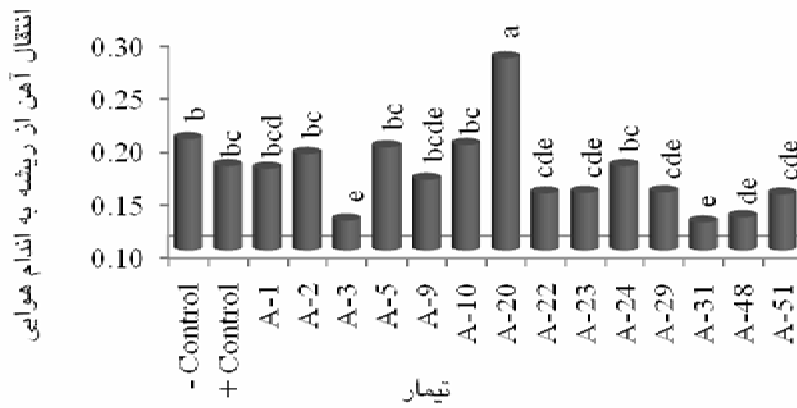


a.#JC OI\*, T DA< [ - +\*#X- ;<\$%&'!( )^\* B(A- G&T?1, ) ;?\_MG&TV2U@2- ?W1&X- -8 O54

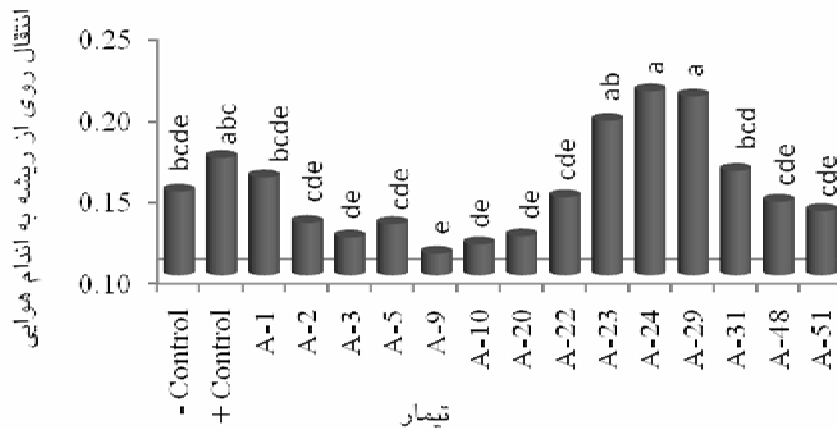


a.#JC ?Z1+ [ - +\*#X- ;<\$%&'!( )^\* B(A- G&T?1, ) ;?\_MG&TV2U@2- ?W1&X- -9 O54

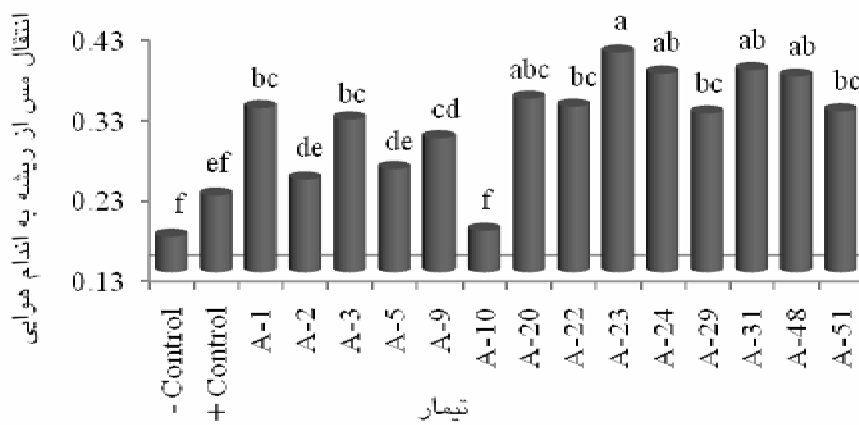




. a#JC OI\*, T DA<?<?ZI+ E\* VTF !&X(@;< \$%%&'()\*^ B(A- G&T?1, ) ;?\_MG&TV2U@2- ?W1&X- -10 O54



. a#JC OI\*, T DA<?<?ZI+ E\* G"+ !&X(@;< \$%%&'()\*^ B(A- G&T?1, ) ;?\_MG&TV2U@2- ?W1&X- -11 O54



. a#JC OI\*, T DA<?<?ZI+ E\* [ - !&X(@;< \$%%&'()\*^ B(A- G&T?1, ) ;?\_MG&TV2U@2- ?W1&X- -12 O54

,G; 17 /-4% 0j N6qB! /\$Q,?" B / ,[q ` S\*\ E%  
-@\*2 04\$P ,H \$dGI -4% 0j (# ,K "\*"d? =\$d B J+  
-,#\*+ (# C+\*2 =gBOG@ Y#g\* <\*d J@e2 B !\*AB! -@+  
.J+ :"\*H \$Q

&T?Z1+ " O1\*, T DA<6JUJ- +\*#X- " =HB1  
96p6% ! -0% B J>[q ! "N6u% 0@2 5-s J[s  
!\*4 (# -#; :\$@ /\$Q, D#! 96p6% J>[q B N# \*Q ) ZH  
,H ! Mn<sup>2+</sup>-? \*2N% /"B-I \$2 ) \* !"#%&, K "\*" ; 0@JF2  
L\*[E% JZ+ ! \$@UH 50A Mn<sup>4+</sup>, K -6K -@JK Mn<sup>4+</sup>  
f, D#! 3 04 ! " !\*AB! -@+ !\* . I aq!N[s l< J+  
(.1376 " &0(r N[s) J+ ,GAS@ ) #9A Mn kl.  
N?& ,#% ,K -?"OK +! 97 (1383) = !hdQ B !\* ) N[s  
! /! " N6u% 0j \_@+ /OH 96p6% ! -0% OH ) \* !"#%&  
,K -?" " =D? (1977) (@+ B \$d2 " (@tdQ ." -? =D?  
kl. cH\$0 /\$Qch; fX\$P ! " (Q' = 9@% ) #9A \$H  
!\*AB! -@+ !\* . I \$dGI l<-H\$#N% ) Q\$K T#-; 96p6%  
{?% :-; X\$P (Q' =-; cl \_1+ ,K ,D#! 3 04 ! "  
.J+ :-; :\$@ ,[@+B ,H Mn kl. &

&T?Z1+ " O1\*, T DA<G"+ +\*#X- " =HB1  
:\$@ ,D#! B N# \*Q ) ZH /B! ! -0% B J>[q  
.JAS# ) #9A /OGK\$H /\$Q, #\*+ NPOH !\* . I ! " 5-67  
Vh[WdK c@dD2 ,H /OGD@ c#\$d2 \$Q! \*AB! -@+ ,. \*2 \$H  
-?! " ! 0r \$6s Op#" \$H /OGdK c#\$d2 B Y#0A (Q' \$H  
Vh[WdK c@dD2 OGdK c#\$d2 c@ " ,H "B! N% L\$dGI  
) #9A (# ! " /Op#" /\$Q! \$KB&\$+ f/B! \$H !\*AB! -@+  
\$D .J+ :"\*H c@P" 5-67 :\$@ ! " /B! ! -0% B J>[q  
) ZH J1e% -Q\$; ! \$d@ /B! ! -0% B J>[q ) #9A  
"OK 0@JF2 (@i (# = \*2N% ! 5-67 :\$@ ,D#! B N# \*Q  
JAS#! " ! :B {16% & =gBOG@ "\*"K \$b62 ! \$d@ (# = \*i ,K  
,H \$dGI J+ :"\*H /OGK\$H N?& ,#% =B-H B : "OK  
(@tdQ B /B! \$H =gBOG@ (@ J1e% ) 6hdQOH 04\$P  
` OG@ 0j OH :!B "\*"K !\* . I ! " OF+B9#! pH ) Q\$K  
/B! ! -0% B J>[q \$2 :-; \_1+ 5\* @\*% ' kl. B /&\$+  
-H\$# ) #9A ! \$d@ (# ! " 5-67 :\$@ ,D#! B N# \*Q ) ZH

564

+ ,7"+#2) #2L, MN\*, M

/ OH ! \$7'-CAS C@E% N7-?! "\$&H 0j 3]P OH  
,H ! "\$0 '# # () ) \* !"#%& f= ! -?\$. 9#! & /" -u2  
5-s \$# N#\$? \*2 ^\* ' B ,H B J+ C@E% (# /B! OH -; !  
N#\$ .!) -Q"N% =D? " \*P & ! !\*AB! -@+ -@\*2 N#\$? \*2  
: ! \$d; , #\*+ \$b62 \$Q, #\*+ 5\$d2 (@ & .(1386 = !hdQ B  
-; ! ,H ! "\$0 ! \$7'-CAS NH\$ZG? JDK C@E% ! " Y#  
(# C+\*2 !\*AB! -@+ -@\*2 5-s :-6Q" =D? ,K "\*"1?  
/\$Q, #\*+ -Q"N% =D? , [r \$! n#\$G? .J+ , #\*+  
N+!OH (# ! " : "\$FG+ " !\*% '# # () ) \* !"#%&  
Y# ! " .-?! " !\*AB! -@+ -@\*2 ! " NH\*P \$G1U? J@H\$0  
-, #\*+ ,K -?" " =D? (1386) = !hdQ B N#\$ . ! N+!OH  
& :-; /&\$+ -. N%\*H '# # () ) \* !"#%& /\$Q  
\$G1U? N#\$? \*2 /! \$@ZH B L\$E% ! \$bi = \$G+ /\$bK\$P  
-@\*2 N#\$? \*2 (@tdQ .-?! " !\*AB! -@+ -@\*2 ! " NH\*P  
N%\*H '# # () ) \* !"#%& /\$Q, #\*+ !\*AB! -@+  
(1996) = !hdQ B \$m?\*+ C+\*2 = \$G+B-6Q /\$bK\$P  
.J+ :-; +! 97

&T?Z1+ " O1\*, T DA<VTF +\*#X- " =HB1  
-, #\*+ !\* . I ! " 5-67 :\$@ (Q' ! -0% B J>[q  
(# .JAS# ) #9A '# # () ) \* !"#%&) [GZ% /\$Q  
! " N# \*Q ) ZH \$r \*\ Z% (Q' ! -0% B J>[q ) #9A  
/\$Q, #\*+ 0#\$+ \$H , U#0% ! " 20 B 2 /\$Q, #\*+ !\* . I  
9@ 2 B 1 /\$b[h; ! " ,K ! \*x? \$dQ ." \*H OGD@ Op#"  
!\*AB! -@+ -@\*2 = \*2 & \$Q, #\*+ (# "\*" ; N% :-Q\$D%  
\$Q! \*AB! -@+ f, h6# ,H ,. \*2 \$H .-?"\*H ! " !\*POH N#\$SH  
(500-2000 Da) aK N<\*h<\*% =&B \$H N< N2\$1@K02  
Nr \$ \ GP B #-; N1@K02 c@% \$H /\$Q-? \$p@ ,K -6GUQ  
,H J1U? /OGdK c#\$d2 B N6@0~ , + (Q' \$H -?\*@ /OH  
0>? ,H f(1999 = !hdQ B M07]@) -?! " ` 9[A 0#\$+  
:\$@ (Q' ! -0% B J>[q ) #9A c#S" & N# -+ ! N%  
\$H (1993) \$? \$#!' (d@DKS .J+ :"\*H !\*AB! -@+ -@\*2  
=gBOG@ Y#g\* <\*d J@e2 B !\*AB! -@+ -@\*2 N+!OH  
/\$bK\$P N%\*H '# # () ) \* !"#%& /\$Q, #\*+  
OH \$Q, #\*+ (# N?& ,#% ,K "OK :-Q\$D% = \$G+B-6Q

DA< ?< ?Z1+ E\* [ - " G"+ \6JU- \VTF ;9&K !&X(@  
 O1\*,T  
 Or \$6s L\$0G? OH /! "N6u% Oj /OGK\$H N?& ,#\$\$  
 \$b62 B J; 17 N# \*Q ) ZH ,H ,D#! & V% B /B! f(Q'  
 ."\*H ! "N6u% Oeq /OGK\$H N?& ,#\$\$ Oj 96p6% " ! \*% !"  
 ,D#! & (Q' L\$0G? ! " Oj | % /\$Q, #\*+ ,K ` ! \*r (#-H  
 /\$Q, #\*+ 9@ ! \*AB! -@+ -@\*2 2\$E< & N# \*Q ) ZH ,H  
 \$H 20 ,#\*+ \$r \* \ Z% \$Q, #\*+ (# DQ\$~ .-? " \*H O2OH  
 20 ,#\*+ ! \* . I ! " \$Q, D#! (Q' ! -0% ,h6# ,H ,. \*2  
 \_1+ \$Q, D#! 3 04 -; ! XOE% " \*% -@\*2 \$H " \*H OGdK  
 -N% N# \*Q ) ZH ,H \$Q, D#! & O \ 6s (# OGbH L\$0G?  
 ,H ,D#! & V% B /B! Or \$6s L\$0G? " ! \*% ! " .-? \*;  
 : " \*H c@P" /Op# " /\$Q! \$KB&\$+ \$SdGI N# \*Q ) ZH  
 /\$Q-@+ C+ \*2 -? \*2N% \$b? \* @ \$K L\$0G? \$r + \$+ .J+  
 ."\* ; c@U2 N< /\$Q-@+ \$# B N[ @JK\*HOK ,6@'  
 fB12 fB6 fB2 fB1 /\$Q( @ \$G#B JPS+ N# \$? \*2 ) \* ! "#\$%&  
 -6? \$% N< /\$Q-@+ B f-@+ Y@ @ \* h@ f-@+ Y@ @ \* G? \$)  
 B 96@ ! \$% ) " ! " ! Y#0G@+ -@+ B Y@ \$% -@+  
 ,6@' /\$Q-@+ (GP\$+ ,H ! " \$0 ( @tdQ .(1996= ! \$hdQ  
 f( @GU@+ f( # - @U@ f= \$A\* G#W02 f( #9@ f( @ #g! ' -6? \$%  
 9)\* < -9< 9? \*7) -; \$HN% -@+ Y@ \$2\* [7f-@+ Y@ @ d\$)  
 /\$Q, D#! " \*% (# ! -0% ,K " \*d? ! \* \ 2 = \*2N% .(1983  
 (# L\$1? " ,H B -H\$N% ) #9A ) \* ! "#\$%&' \$H :-; N?& ,#\$\$  
 -N% OGD@H N# \*Q /\$Q ) ZH ,H " \*% (# L\$0G? f) #9A  
 ( @tdQ .-6\$sd?N% cdI " \*P : OdQ ! \$b? \*# B " \* ;  
 ,#\$\$ = \$Q\$@ ! " N# \*Q /\$Q ) ZH ,H Or \$6s OGD@H L\$0G?  
 -6? \$% N? \*% ! \*Q N-\$dGI Oj ,H ) \* ! "#\$%&' \$H :-; N?&  
 XOE% c% \*s = \*6s ,H ! \*A! -@+ Oj 9@ B ( @ @ \* G@+  
 -; ! Y#0E2 (d' ,K " \* ; N% : " " J1U? : \$@ -; !  
 N# \*Q /\$bDZH ,H /! B0' /\$b? \*# J# -Q \_1+ ,D#!  
 B -6[H N. \$I .(1989 = ! \$hdQ B \* < \*2 96@ ! \$% ) " \* ; N%  
 B" ! " ) \* ! "#\$%&' N#g\* < \*K N+ ! OH \$H (1383) = ! \$hdQ  
 L\$0G? OH = ' N?& ,#\$\$ Oj B = \$m# \$H ! 1' Nu20% ,ox6%  
 ,K -? " " = \$D? 5-67 : \$@ ! " a@+ \$G) B = gB0G@ Or \$6s  
 ) ZH ,H ,D#! & Or \$6s (# L\$0G? OH \$QOGK\$H \*2 &  
 ` \$1@K02 N-\$dGI Oj ,H ! = ' B -? ! " NG1e% O@j2 N# \*Q  
 ) ZH ,H " \*P \$H ! Or \$6s (# ,K ,D#! :-; -@\*2 N<  
 .-? " " J1U? -6Q" N% L\$0G? NR \*Q

) [GZ% /\$Q, #\*+ N?& ,#\$\$ Oj .(1990 J7\$H B \$%! B)  
 ! " /B! ! -0% B J>[q ) #9A OH ' # # ( ) \* ! "#\$%&  
 :-; + ! 97 / " # & = \$00E% C+ \*2 ` ! 1 B 5-67 = \$Q\$@7  
 = ! \$hdQ B NA O@+ f1386 = ! \$hdQ B N# \$ . ! ) J+  
 .(2008 " \*7 f2006  
 &T?Z1+ " O1\*,T DA< [ - + \*#X- " = HB1  
 J>[q ) #9A OH /OGK\$H N?& ,#\$\$ Oj ,K -6i OQ  
 ! "N6u% 5-67 : \$@7 ,D#! B N# \*Q ) ZH V% ! -0% B  
 , @H 10 ,#\*+ \$r \* \ Z% \$Q, #\*+ NPOH 9. ,H N-B " \*H  
 B J1e% -Q\$; /\$Q! \$d@ \$H /! "N6u% ` B\$F2 \$Q, #\*+  
 ! -0% B J>[q " ! \*% ! " \$r \* \ Z% .-6G; -? NF6% -Q\$;  
 B J>[q OH NF6% Oj , @H 10 ,#\*+ 9. ,H ,D#! V%  
 ! " V% ,K \$m? ' & .-? " \*H ,G; 17 ,D#! V% ! -0%  
 /! -# \$) ! \$@UH Vh[WdK N< " \*% " # & ! -0% ! \* . I  
 f(1378 N2\*h[ ] " \* ; N% -. NGZ+ ,H B -Q" N% c@hD2  
 & Nr \$P N< ` \$E; 02 /OUh# \$QOGK\$H \*2 & \$SdGI  
 c@hD2 V% \$H B -? ! " /- @ \* K \*% B /- # ! \$K\$+ N[ ] ,d.  
 ! \*AB! -@+ ! \* . I aq! N[s l< : " " N# \*0 ! \$@UH Vh[WdK  
 ) #9A " # & : \$@7 V% ! -0% B J>[q ,D#! 3 04 ! "  
 N6[K /! " ,K 10 ,#\*+ -+ ! N% 0>? ,H .J+ ,GA\$@  
 l< B : "OK , ; 02 /OGdK B -# ! \$K\$+ N[ ] : " \*H NhDP  
 (# ! \* . I ! " N# \*Q ) ZH B ,D#! V% ! -0% B J>[q  
 Oj (2009) = ! \$hdQ B /BOUP .J+ : " \*H OGD@H ,#\*+  
 /\$Q L\$b? OH ! ' # # ( ) \* ! "#\$%&' ,#\*+ 4 N?& ,#\$\$  
 f, #\*+ 4 ( @ ! " ,K -? "OK + ! 97 B N+ ! OH \_@+ = \* .  
 Or \$6s kl. ) #9A OH ! O@j2 (# OGD@H AFA146 ,#\*+  
 Mn fK fP fN B \_@+ /OH B B Zn fMn fFe fMg fK  
 ,#\$\$ Oj ,K N-\$I ! " .J; " \_@+ /\$Q L\$b? ,D#! Zn B  
 = ! \$hdQ B ! \* } N[s . " \*H O@j2 NH V% kl. OH N?&  
 ,h@ \$I ! " .-? "OK + ! 97 ! NbH\$D% n# \$G? (1383)  
 N?& ,#\$\$ Oj (2008) " \*7 B (2006) = ! \$hdQ B NA O@+  
 = \$Q\$@7 ! " V% ! -0% B J>[q OH ! ) \* ! "#\$%&' /OGK\$H  
 .-? " \*d? + ! 97 ! " N6u% B J1e% ` ! 1 B 5-67

-\$90: " -, ./ 74\$8/

,#% Oj B =\$m#\$H!1' Nu20% ,ox6% B" !" ) \* !"#%&N#g\* <\*K N+!OH .1383f& OA0b% B = " &O(r N[s f! -6[H N. \$I  
f5B" :!\$d; fa6DQ L\$+. Nu@4 {H\$6% B /&!B\$DK =\*6A B 5\*[s .5-67 :\$@7 N?-u% ,#I (2 B -; ! /B! = ' N?&  
.75-90 /\$Q, EFr

f-; ! /B! '# # O ) \* !"#%& N%\*H /\$Q, #\* + -; ! X0E% /\$Qc@J?\$G) Oj .1386 f3 NU@! f^ N?\$Z@s fM N#\$. !  
ah# B cbi :!\$d; .aQ"&\$# L\$+ .Nu@4 {H\$6% B /&!B\$DK =\*6A B 5\*[s .5-67 ! " N# lq Or \$6s kI. B "Oh[ds  
.285-287 /\$Q, EFr .(k)

B (Q' (@y2 ! " ! \*AB! -@+ : -66K -@\*2 /\$QM\$?\*B"\* + B \$Q! \*AB! -@+ \*G@ ) o? N+!OH .1384 f^ 5 N?\$@-r N<\*+!  
.M! -% J@I02 :\$pD? " f/&!B\$DK :-hD? " f/OGK" , \$+! .5-67 5\$0! &\$@ " ! \*% /B!

-393 /\$Q, EFr .9#012 :\$pD? " ` ! \$DG? .5B" 3#i .(, d. 02)X\$P Nd@, \*@ B /g\* <\*@B0h@ .1376 f= " &O(r N[s  
.391

!" \_@+ L\$b? ,#I (2 B -; ! OH ) \* !"#%& Y#g\* <\*@ " \*K 0@j2 N+!OH .1383 f: /BOUP B \* 5 N2\*h[% f` & ! \*)N[s  
a+ B " \*K & ,6@H :"\$FG+ B Y#g\* <\*@ " \*% "OH!\$K / ,u+ \*2 N[% ) #dQ (@\*+ ` S\$0% ,r ]P .NhQ' /\$bK\$P  
.299 300 /\$Q, EFr . /&!B\$DK + &\*%' OD? . \*OK . /&!B\$DK !"

,H '#+ "(, -. & a#9?' (# =g L\$0G? Nm6+ =\$h% B N%\*H /\$QOGK\$H\*2& &\$6@'" -ACC J@uA N+!OH .1388 f" : " &\*OA  
.9#012 :\$pD? " . /&!B\$DK :-hD? " . /OGK" , \$+! .) \* !"#%&

0@j2 \$H "OP Or \$6s " /&!B\$DK ` S\*\ E% J@K " \*1bH B "Oh[ds ) #9A ! " \$Q/I (% 9#! ) o? .1378 f\* 5 N2\*h[%  
.70-221 :/\$Q, EFr .43 :!\$d; .M! -% J@I02 :\$pD? " ` ! \$DG? . " =]K

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