REFERENCES


Mo. and Li., 1992. Quantity of heavy metals and other dreadful contaminants, heavy metals show deleterious effects on cell division of plants. *Tropical Plant Research* 14:9-61.


PUBLICATIONS
PUBLICATIONS


Welcome to ISRJ

Indian Streams Research Journal is a multidisciplinary research journal, published monthly in English, Hindi & Marathi Language. All research papers submitted to the journal will be double - blind peer reviewed referred by members of the editorial board. Readers will include investigator in universities, research institutes government and industry with research interest in the general subjects.

International Advisory Board

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution/University</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flávio de São Pedro Filho</td>
<td>Federal University of Rondonia, Brazil</td>
</tr>
<tr>
<td>Kamani Perera</td>
<td>Regional Center For Strategic Studies, Sri Lanka</td>
</tr>
<tr>
<td>Janaki Simnamsamy</td>
<td>Librarianian, University of Malaya</td>
</tr>
<tr>
<td>Romona Mihaia</td>
<td>Spiru Haret University, Romania</td>
</tr>
<tr>
<td>Delia Serbescu</td>
<td>Spiru Haret University, Bucharest, Romania</td>
</tr>
<tr>
<td>Anurag Misra</td>
<td>DBS College, Kanpur</td>
</tr>
<tr>
<td>Titus PopPhD</td>
<td>Partium Christian University, Oradea,Romania</td>
</tr>
<tr>
<td>Mohammad Haileat</td>
<td>Dept. of Mathematical Sciences, University of South Carolina Aiken</td>
</tr>
<tr>
<td>Abdullah Sabbagh</td>
<td>Engineering Studies, Sydney</td>
</tr>
<tr>
<td>Catalina Neculai</td>
<td>University of Coventry, UK</td>
</tr>
<tr>
<td>Ecaterina Patrascu</td>
<td>Spiru Haret University, Bucharest</td>
</tr>
<tr>
<td>Loredana Bosca</td>
<td>Spiru Haret University, Romania</td>
</tr>
<tr>
<td>Fabricio Moraes de Almeida</td>
<td>Federal University of Rondonia, Brazil</td>
</tr>
<tr>
<td>George - Calin SERITAN</td>
<td>Faculty of Philosophy and Socio-Political Sciences Al. I. Cuza University, Iasi</td>
</tr>
<tr>
<td>Hasan Bakir</td>
<td>English Language and Literature Department, Keyseri</td>
</tr>
<tr>
<td>Ghayoor Abbas Chotana</td>
<td>Dept of Chemistry, Lahore University of Management Sciences[PK]</td>
</tr>
<tr>
<td>Anna Maria Constantinevici</td>
<td>AL. I. Cuza University, Romania</td>
</tr>
<tr>
<td>Ilie Pintea</td>
<td>Spiru Haret University, Romania</td>
</tr>
<tr>
<td>Xiaohua Yang</td>
<td>PhD, USA</td>
</tr>
</tbody>
</table>

Editorial Board

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution/University</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pratap Vynmtrna Naikwade</td>
<td>ASP College Dehradun,Ratangiri,MS India</td>
</tr>
<tr>
<td>R. R. Patil</td>
<td>Head Geology Department Solapur University,Solapur</td>
</tr>
<tr>
<td>Rama Bhosale</td>
<td>Prin. and Jt. Director Higher Education, Panvel</td>
</tr>
<tr>
<td>Salve R. N.</td>
<td>Department of Sociology, Shivaji University,Kollapur</td>
</tr>
<tr>
<td>Govind P. Shinde</td>
<td>Bharati Vidyapeeth School of Distance Education Center, Navi Mumbai</td>
</tr>
<tr>
<td>Chakane Sanjay Dnyaneeshwar</td>
<td>Arts, Science &amp; Commerce College, Indapur, Pune</td>
</tr>
<tr>
<td>Awadhesh Kumar Shirotriya</td>
<td>Secretary,Play India Play,Meerut(U.P.)</td>
</tr>
<tr>
<td>Iresh Swami</td>
<td>Ex - VC. Solapur University, Solapur</td>
</tr>
<tr>
<td>N S. Dhaygude</td>
<td>Ex. Prin. Dayanand College, Solapur</td>
</tr>
<tr>
<td>Narendra Kada</td>
<td>Jt. Director Higher Education, Pune</td>
</tr>
<tr>
<td>K. M. Bhandarkar</td>
<td>Praful Patel College of Education, Gondia</td>
</tr>
<tr>
<td>Sonal Singh</td>
<td>Vikram University, Ujjain</td>
</tr>
<tr>
<td>G. P. Patankar</td>
<td>S. D. M. Degree College, Honavar, Kamataka Shashiya Snatkorrt Mahavidyalaya, Dhar</td>
</tr>
<tr>
<td>Maj. S. Bakhtiar Choudhary</td>
<td>Director,Hyderabad AP India.</td>
</tr>
<tr>
<td>S. Parvathi Devi</td>
<td>Ph.D.-University of Allahabad</td>
</tr>
<tr>
<td>Sonal Singh</td>
<td>Vikram University, Ujjain</td>
</tr>
<tr>
<td>Rajendra Shendge</td>
<td>Director, B.C.U.D. Solapur University, Solapur</td>
</tr>
<tr>
<td>R. R. Yalikar</td>
<td>Director Management Institute, Solapur</td>
</tr>
<tr>
<td>Unmesh Rajderkar</td>
<td>Head Humanities &amp; Social Science YCMOU,Nashik</td>
</tr>
<tr>
<td>S. R. Pandya</td>
<td>Head Education Dept. Mumbai University, Mumbai</td>
</tr>
<tr>
<td>Alka Darshan Shrivastava</td>
<td></td>
</tr>
</tbody>
</table>

Address:- Ashok Yakkaldevi  258/34, Raviwar Peth, Solapur - 413 005 Maharashtra, India
Cell : 9595 359 435, Ph No: 02172372010 Email: ayisrj@yahoo.in Website: www.isrj.net
Aluminium Phytoremediation Potential of Pedilanthus Varieties

K. Sujatha1 and Santosh Kumar Mehar1,2

1Department of Botany, Sri Venkateswara University, Tirupati A.P. India.
2Department of Botany, J.N.V. University, Jodhpur, Rajasthan, India.

Abstract: Al toxicity is an important limitation to worldwide crop production, which is more prevalent in acidic soils. Since 8% of the world’s potentially arable lands are acidic, the problem needs more attention. Therefore the present study was undertaken to evaluate the Al remediating potential of Pedilanthus varieties. Plants were grown in various concentrations of AlCl3 treated soils for 12 weeks. Root and shoot lengths were measured and recorded. Al accumulated and remained in plants and soil respectively was quantified using inductively coupled plasma-optical emission spectrometry (ICP-OES). Results of the present study revealed high accumulation of Al in both the varieties of Pedilanthus without any signs of Al toxicity in terms of root and shoot lengths. Therefore both the varieties may be used to combat Al toxicity and protect the crop plants from loss of productivity.

Keywords: Aluminium Phytoremediation Potential, acidic soils, after oxygen and silicon.

INTRODUCTION

Aluminium (Al) is the third most abundant metallic element in soil after oxygen and silicon. It is largely present in the form of aluminosilicate minerals, and so very small quantities appear in the soluble form, capable of affecting biological systems (May and Nordstrom, 1991). Al bioavailability for plants and its toxicity is a major constraint for crop production in acidic soils worldwide. When the soil pH drops below 5, Al3+ ions are released in to the soil and enter into root tip cells ceasing the root growth. So, the main target of Al is the root tip. It causes inhibition of cell elongation and cell division, leading to root stunting accompanied by reduced water and nutrient uptake. At tissue level, the distal part of the transition zone is most sensitive to Al. Many cell components are implicated in the Al toxicity including DNA in nucleus, numerous cytoplasm compounds, mitochondria, the plasma membrane and the cell wall at cellular and molecular level.

Many of the agricultural practices such as removal of products from the farm, leaching of nitrogen below the plant root zone, inappropriate use of nitrogenous fertilizers, and build-up in organic matter, are causing acidification of agricultural soils. Therefore production of staple food crops, in particular grain crops, is badly affected (Kochian et al., 2005). Due to these drawbacks, phytoremediation technologies are continuously being researched for possible solutions.

In spite of lot of researches done on many plants and many metals, the studies on phytoremediation of Aluminium are comparatively overlooked aspect. Pedilanthus tithymaloides belonging to the family, Euphorbiaceae is a small tropical shrub. The two varieties of Pedilanthus viz., Pedilanthus tithymaloides var. variegatus and P. tithymaloides var. tithymaloides were studied by Jamil et al. (2009) for their dust trapping and metal accumulation capacity in their leaves when they were grown at road side. They reported accumulation of Fe, Zn, Cu, Cd, Ni, Mn and Cu efficiently among the 10 plant species chosen for their
work. Hence, in the present study the phyto Remedation potential of Pedilanthus varieties for Al was assessed.

MATERIALS & METHODS

1. Collection of plant materials

Two varieties of Pedilanthus tithymaloides were collected from the Botanical garden, S.V.University, Tirupati and the identification was confirmed with taxonomist, Department of Botany Sri Venkateswara University, Tirupati, A.P., India. Voucher specimen was deposited for future reference.

2. Experimental procedure

Pedilanthus var.. A (Pedilanthus tithymaloides L. var. variegatus) Pedilanthus var B (Pedilanthus tithymaloides L. var. tithymaloides) stem cuttings of 8g weight were planted in plastic pots containing 500g of sieved soil (sieved through 2mm pores). The pots were grouped (n=3) in to C-Control,1-100ppm,2-200ppm,3-300ppm,4-400ppm,5-500ppm based on Al treatments. To the treatment groups Aluminum chloride solution was added at their respective concentrations. All the groups were allowed to grow for 12 weeks and at the end plants were harvested, the root and shoot lengths were measured using scale. Plant biomass and soil of each group was retained and stored for estimation of Al accumulated and remained in them respectively.

3. INDUCTIVELY COUPLED PLASMA-OPTICAL EMISSION SPECTROMETRY (ICPOES)

Sample preparation by microwave digestion method

Sample preparation of plant and soil samples was carried out by microwave digestion system (CEM corporation ltd.). Approximately 1 g (dry mass) of the sample was weighed directly into the PTFE vessels, to which 10 mL of concentrated HNO₃ was added and the vessels were capped immediately. The digestion programme consisted of a ramp time of 10 min to reach 150 °C and a dwell time of 10 min at 150 °C. The power was 800 W. After the completion of programme, vessels were cooled, vented and opened and then 2mL of 30% H₂O₂ was added, and the solution was filtered into 25 mL volumetric flasks and the volume was made up with double distilled water. Blanks were prepared by following similar digestion procedure without plant or soil sample. These digested samples (plant or soil) were subjected for quantification of Al and other soil nutrients by ICPOES.

RESULTS & DISCUSSION

1. Al ABSORBED BY PEDILANTHUS VARIETIES

In both the varieties of Pedilanthus the amount of Al absorbed was found to increase significantly from 1st to 2nd concentration and then decreased at 3rd concentration and then decreased at 3rd concentration followed by an increase from 3rd to 5th concentration as shown in the Table-1 and Figure-1. This shows the Al accumulating ability of both the varieties of Pedilanthus. The ANOVA data indicate that both the varieties are equally effective in accumulating Al Table-2, however, the accumulation capacity among the two were not statistically different from each other.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Pedilanthus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Var. A</td>
</tr>
<tr>
<td>1</td>
<td>17.82±5.34</td>
</tr>
<tr>
<td>2</td>
<td>22.15±2.75</td>
</tr>
<tr>
<td>3</td>
<td>18.83±0.93</td>
</tr>
<tr>
<td>4</td>
<td>20.39±2.89</td>
</tr>
<tr>
<td>5</td>
<td>22.46±7.56</td>
</tr>
</tbody>
</table>

Table-1 Amount of Al absorbed by Pedilanthus varieties
Table 2 Analysis of variance results of Aluminium content in two varieties of Pedilanthus

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>Computed f</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replication</td>
<td>2</td>
<td>2.914</td>
<td>1.457</td>
<td>0.133</td>
<td>ns</td>
</tr>
<tr>
<td>Varieties</td>
<td>1</td>
<td>18.003</td>
<td>18.003</td>
<td>1.645</td>
<td>ns</td>
</tr>
<tr>
<td>Error a</td>
<td>2</td>
<td>21.884</td>
<td>10.942</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration of Aluminium</td>
<td>4</td>
<td>60.283</td>
<td>15.071</td>
<td>1.277</td>
<td>ns</td>
</tr>
<tr>
<td>Error b</td>
<td>8</td>
<td>94.424</td>
<td>11.803</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction between Varieties and concentration of Aluminium</td>
<td>4</td>
<td>32.529</td>
<td>8.132</td>
<td>0.431</td>
<td>ns</td>
</tr>
<tr>
<td>Error c</td>
<td>8</td>
<td>151.084</td>
<td>18.885</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
<td>11972.66</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. Al REMAINED IN SOIL AFTER PHYTOREMEDIATION WITH PEDILANTHUS VARIETIES

Table 3 and Figure 2 indicates that in both the varieties of Pedilanthus, there was a significant decrease in soil Al content of all the treated groups after phytoremediation. This shows that both the varieties are capable of absorbing Al from soil. ANOVA data reveals that there was no significant difference between soils’ Al content of both the varieties Table 4.
Table 3: Amount of Al remained in soil after phytoremediation with Pedilanthus varieties

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Variety A</th>
<th>Variety B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80.53±2.85</td>
<td>80.77±2.82</td>
</tr>
<tr>
<td>2</td>
<td>166.50±4.27</td>
<td>169.87±5.49</td>
</tr>
<tr>
<td>3</td>
<td>279.41±3.30</td>
<td>280.12±3.79</td>
</tr>
<tr>
<td>4</td>
<td>360.32±4.93</td>
<td>358.43±4.13</td>
</tr>
<tr>
<td>5</td>
<td>455.47±4.85</td>
<td>457.43±3.57</td>
</tr>
</tbody>
</table>

Table 4: Analysis of variance results of Aluminium content of soil with two varieties of Pedilanthus

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Sum of squares</th>
<th>Mean squares</th>
<th>Computed f</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replication</td>
<td>2</td>
<td>8717.75</td>
<td>4358.875</td>
<td>1.107</td>
<td>ns</td>
</tr>
<tr>
<td>Varieties</td>
<td>1</td>
<td>353.5</td>
<td>353.5</td>
<td>0.0876</td>
<td>ns</td>
</tr>
<tr>
<td>Error a</td>
<td>2</td>
<td>3875.75</td>
<td>1937.875</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration of Aluminium</td>
<td>4</td>
<td>5799.5</td>
<td>1449.875</td>
<td>0.313</td>
<td>ns</td>
</tr>
<tr>
<td>Error b</td>
<td>8</td>
<td>37065.25</td>
<td>4632.657</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction between Varieties and concentration of Aluminium</td>
<td>4</td>
<td>29851.5</td>
<td>7462.875</td>
<td>2.900</td>
<td>ns</td>
</tr>
<tr>
<td>Error c</td>
<td>8</td>
<td>20384.25</td>
<td>2543.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
<td>2244</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. EFFECT OF AL ON ROOT GROWTH

Figure-3 indicates that in *Pedilanthus* var A, there was a decrease in the length of adventitious roots from 1st to 5th concentration when compared to control. But the numbers of roots were found to increase in treated plants when compared with control. Maximum numbers of roots (8) were observed at 3rd concentration.

Figure-4 indicates that in *Pedilanthus* var B, there was an increase in number of roots from 1st to 5th concentration when compared with control. At 3rd concentration maximum root length was observed when compared to the control plants.

4. EFFECT OF Al ON SHOOT LENGTH

In case of *Pedilanthus* var A, Shoot length increased from 1” to 3” concentration but decreased in 4” and again increased in 5” concentration in comparison to control, as shown in Figure-5. In case of *Pedilanthus* var B, same trend was observed with respect to shoot length (Figure-6).
DISCUSSION

It is well known that some plant species can accumulate high concentrations of Al without showing symptoms of Al toxicity (Jian Feng Ma et al., 2001). This Al resistance depends on the ability of the plant to tolerate Al in symplast or to exclude it to soil (Taylor, 1991). In the present study two varieties of *Pedilanthus* viz., *P. tithymaloides* var. variegatus and *P. tithymaloides* var. *tithymaloides* were analysed for their ability to accumulate and resist Al.

In both the varieties of *Pedilanthus* the amount of Al absorbed increased from 1° to 2° concentration and then decreased at 3rd concentration followed by an increase from 3rd to 5th concentration when compared to the control plants. The decrease at 3rd concentration could possibly indicate the threshold of plant species for Al toxicity. Increased absorption after 3rd indicates its adoptability beyond 300ppm. The accumulation levels observed in both the plants indicate that they are hyper accumulators of Al. The ANOVA data indicated that both the varieties are equally effective in accumulating Al.

The reasons for the tolerance of Al toxicity by plants are many; for example, organic acids play a central role in Al tolerance mechanisms. Some plants detoxify Al in the rhizosphere by releasing organic acids that chelate Al. In at least two species, wheat and maize, the transport of organic acid anions out of the root cells is mediated by Al-activated anion channels in the plasma membrane. Other plants, accumulate Al in their leaves, detoxify Al internally by forming complexes with organic acids.

Another set of mechanisms are; Malate which is released from the roots of Al-tolerant cultivars of wheat.
Aluminium Phytoremediation Potential Of Pedilanthus Varieties

(Delhaize et al., 1993), citrate from Al-tolerant cultivars of snapbean (Miyasaka et al., 1991), maize (Pellet, 1995), Cassia tora (Ma et al., 1997) and soybean (Yang et al., 2001); and oxalate from buckwheat (Ma et al., 1997) and taro (Miyasaka et al., 1991). There was a significant decrease in soil Al content of all the treated groups after phytoremediation. This can be naturally expected because Al accumulation in plant increased. Therefore, we can emphasize that both the varieties are capable of absorbing Al from soil and accumulate in them.

Regarding root length, although there was a decrease in the length of adventitious roots from 1st to 5th concentration when compared to control plants, the numbers of roots were found to increase in treated plants. Maximum numbers of roots 8 and 11 were observed at 3rd concentration for variety A and variety B respectively. Under Al toxicity inhibition of root is a visible symptom. In other words, root stunting is a consequence of Al-induced inhibition of root elongation. Roots are usually stubby, brittle. Root tips and lateral roots become thick and may turn brown (Mossor-Pietraszewska et al., 1997). Such roots are inefficient in absorbing both nutrients and water. Young seedlings are more susceptible than older plants. Al apparently does not interfere with seed germination, but does impair the growth of new roots and seedling establishment (Nosko et al., 1988). But these symptoms were not found in the present study.

The most common responses of shoots to Al toxicity include: cellular and ultrastructural changes in leaves, increased rates of diffusion resistance, reduction of stomatal aperture, decreased photosynthetic activity leading to chlorosis and necrosis of leaves, total decrease in leaf number and size, and a decrease in shoot bio-mass or length (Thornton et al., 1986). Both the varieties of Pedilanthus exhibited increased shoot length from 1st to 3rd concentration, decrease at 4th and again increase at 5th concentration when compared to control. Also no other aforesaid symptoms were observed. This trend clearly indicates Al tolerance in both the varieties.

CONCLUSION

Aluminium toxicity is an important growth-limiting factor for many crop plants. Toxicity in such plants is often clearly identifiable through morphological and physiological symptoms finally affecting productivity. Our results had demonstrated that phytoremediation of Al with either of the varieties of Pedilanthus can restore fertility of soils and reduces the effect of Al toxicity on productivity of crop plants

REFERENCES

Dear Sir/Mam,

We invite unpublished Research Paper, Summary of Research Project, Theses, Books and Book Review for publication. You will be pleased to know that our journals are

Associated and Indexed, India

* International Scientific Journal Consortium
* OPEN J-GATE

Associated and Indexed, USA

* Google Scholar
* EBSCO
* DOAJ
* Index Copernicus
* Publication Index
* Academic Journal Database
* Contemporary Research Index
* Academic Paper Database
* Digital Journals Database
* Current Index to Scholarly Journals
* Elite Scientific Journal Archive
* Directory of Academic Resources
* Scholar Journal Index
* Recent Science Index
* Scientific Resources Database
* Directory of Research Journal Indexing

Indian Streams Research Journal
258/34 Raviwar Peth Solapur-413005, Maharashtra
Contact-9595359435
E-Mail-ayisrj@yahoo.in/ayisrj2011@gmail.com
Website: www.isrj.net
TOXIC EFFECTS OF ALUMINIUM IN PLANTS

Sujatha K. and *Santosh Kumar Mehar

1Department of Botany, Sri Venkateswara University, Tirupati, Andhra Pradesh, India
2Department of Botany, J.N.V. University, Jodhpur, Rajasthan, India

*Author for Correspondence

ABSTRACT
Aluminium occurs in the form of oxides and silicates and is the most abundant metal in the earth’s crust. Although it is abundant in earth, its impact on plants and other organisms was not a cause of major concern. However, over the course of time, amount is steadily increasing, primarily in acidic soils. At pH 5 or below, toxic effects of Al are more aggravated. Since over 50% of the worlds arable soils are acidic, Al toxicity is becoming an important limiting factor worldwide to crop productivity. In plants the major site of toxic effect of Al is the apical part of the root. It has been reported that the ultrastructure of root cap cells is affected by Al toxicity. However, the toxic effects are seen in both apoplast and the symplast of many plant species. Even short exposure to Al are reported to cause reduction in the root elongation, thereby limiting the acquisition of water and nutrients from the soil.

Keywords: Aluminium toxicity, Acidic soil, Apical root, Symplasm

INTRODUCTION
In the periodic table, Aluminium (Al) is in group IIIa and has a valency of +3. It shows high reactivity with oxygen at normal temperature. Along with this characteristic, it also reacts strongly with acids and bases to form salts and releases hydrogen. It commonly occurs in the form of oxides and silicates, and is the most abundant metal in the earth’s crust. This metal is the most abundant in the Earth’s crust, naturally absorbed from the soil by plants and foodstuffs. In the form of salts, it has properties that make it a versatile and useful additive. Al sulphate is added to water to improve clarity, all foods that need raising agents or additives, such as cakes and biscuits, contain Al. Children’s sweets contain Al-enhanced food colouring. It is in tea, cocoa and malt drinks, in some wines and fizzy drinks and in most processed foods. It is also part of cosmetics, sunscreens and antiperspirants, and used also as a buffering agent in medications like aspirin and antacids. It is even used in vaccines. Over the course of time however, the amount of Al is steadily increasing. Aluminum toxicity is the primary factor that limits crop production on strongly acidic soils. At soil pH values at or below 5, toxic forms of Al are solubilized into the soil solution, and inhibit root growth and function, and thus reduce the crop yields. It has been estimated that over 50% of the world’s potentially arable lands are acidic (Bot et al., 2000); hence, Al toxicity is a very important worldwide limitation to crop production. Furthermore, since up to 60% of the acid soils in the world occur in developing countries, where food production is critical. Toxicity effects of Al on crops are becoming a major cause of concern for the farmers.

Breeding of crops with increased Al resistance could be considered a way out, however, the underlying molecular, genetic and physiological bases are still not well understood. Because of the agronomic importance of this problem, understanding the mechanism of Al toxicity in plants is very important. The present review is a brief survey of studies related to the toxic effects of Al on the plants.

Bioavailability of Al
According to Exley and Birchall (1992), the bioavailability of a substance is defined as a measure of its potential to interact with biological systems and also the capacity to cause a response. Due to its adsorption to mineral surfaces, bioavailability of Al in soil and water remains very low. At pH near neutral, it forms associations with organic matter and also due to the insolubility of hydroxide complexes of Al, its bioavailability is considered to be very low. However, due to the acidification of soil and water, the presence of Al is being recognized as a major pollution problem. With acid rains also Al is released from its natural reservoirs (Myrold and Nason, 1992). When the pH of the solution is near or lower than
5.0, most of the Al exists as an octahedral hexahydrate Al(H₂O)₆³⁺ (referred to as Al³⁺ or free Al), and at neutral pH it precipitates as Al(OH)₃.

According to Martin (1986), the proportion of different oxidation forms of Al is function of the environmental pH, and even small variations in the acidity of the environment could cause great changes in the concentration of these species. Bruce et al., (1988), a soil with pH ~5.8 has 6.3µM Al. And, when the pH is further lowered to 4.77, the Al level rises to 700 µM. On the contrary, increase in pH to 6.22 reduces the concentration to 5µM. The bioavailability of Al therefore is determined not only by the natural conditions of the soil and pH changes, but also by human activities which can modify the environment through inadequate agricultural procedures or by disposal of wastes in the environment.

Toxicity Effects of Al in Plants

Aluminium is very toxic to living organisms. One of the reason why this is so is that most of the organisms live in a pH range around 7.0, and therefore, have not developed the mechanisms to tolerate high levels of Al. As a consequence of this, when the concentration of Al rises in acidified waters, various ailments in human beings, animals and plants are observed.

Most easily recognized symptoms of Al toxicity in plants is the inhibition of root growth, which is considered to be the most widely accepted measure of Al stress in plants. In nutrient solutions even micromolar concentration of Al begins to inhibit root growth within a short time (~60min). As stated earlier, the forms of Al change rapidly with change in the pH of the soil or water, the form of Al which exerts the toxic effect is difficult to identify. Al rapidly hydrolyzes in solution, as a result the trivalent Al species Al³⁺, dominate in acidic conditions (pH < 5), whereas the Al(OH)⁵⁺ and Al(OH)⁷⁺ species are formed as the pH increases. Since, many trivalent cations are toxic to plants and, because Al toxicity is largely restricted to acid conditions, it is generally believed that Al³⁺ is the major phytotoxic species of Al, however, it could not be concluded with certainty. Kinraide (1991) reviewed that nearly all of the monomeric Al species have been considered toxic in one study or the other.

Site of Al Toxicity in Plants

The apical part of the root which includes root cap, meristem and the zone of elongation are reported to accumulate more Al and as a result suffer greater physical damage than the mature tissues in the root. Ryan et al., (1993) reported that only the apical 2-3 mm of the maize root needed to be exposed to Al when it started to inhibit the root growth. Further, their study made an interesting observation that selective application of Al to the elongation zone or the entire root except the root apex did not cause any reduction in growth. In another study, Bennet and Breen (1991) observed a number of changes in the ultrastructure of the cap cells in maize roots when Al treatment was extended for 2 hours. They concluded that in such situations Al could inhibit root growth indirectly through signal response pathway, which involved root cap, hormones and secondary messengers. This hypothesis thus considers the involvement of root cap in signal perception and hormone distribution. But, it was also recorded by Ryan et al., (1993) that the inhibition of root growth in maize was the same in intact and decapped roots. This points to the important role played by the root meristem in Al toxicity in maize.

Where does the Al start to exert its effect is difficult to prove. Since polyvalent ions (such as Al³⁺) are insoluble in lipid bilayers, the plasma membrane is a barrier to Al entry. Even than it has been observed that some Al crosses the plasma membrane (probably as neutral Al ligand, or by endocytosis, or through membrane bound protein, or due to lesions caused by stress). But an interesting report by Tice et al., (1992) has shown that half of the total Al present in the root apex was located in the symplasm. The absorption of Al has been linked to susceptibility of certain plant species to Al. It has been seen that root apices of Al tolerant wheat (Triticum aestivum) accumulated less Al than Al sensitive wheat genotypes. As reported earlier, exposure to Al for short duration (<60min) could inhibit root growth. One important question that needs to be answered is how quickly Al moves into the symplasm and that too in sufficient quantity to cause the effect. This question was partly resolved when Lazof et al., (1994) detected Al in symplasm of soybean (Glycine max) roots after exposure to 30min only. This proves that Al could enter before the root growth is inhibited, and further that symplasm is probable site of Al toxicity. What needs to be remembered here is that after entry into the symplasm, the prevailing pH there (6.5 to 7.5) and also
the large numbers of potential ligands will probably maintain a very low concentration of Al\(^{3+}\). Therefore, at such low concentration Al could hardly cause significant damage in the symplasm. With this information in the background, it has been suggested that the primary cause of toxicity in the symplasm is the formation of Al-ligand complex. Once this association is formed, Al either inhibits the vital functions earlier performed by that ligand (the ligand could be binding to enzymes, calmodulin, tubulin, ATP, GTP, DNA) or the Al-ligand complex itself could now poison some metabolic process. Apart from entry into the symplasm and the toxicity effects there, Al has very easy and quick access to apoplasms. This way, interaction with cell wall and membrane will preced transport into the symplasm, and interactions here (in the apoplast) could be possibly harmful. In the apoplast, association of Al with pectic residues and/or proteins in the cell wall could decrease the extensibility of cell wall, displace other ions from critical sites on the cell wall or membranes, bind to the lipid bilayer or membrane bound proteins and inhibit nutrient transport, or could disrupt intracellular metabolism from the apoplast itself by triggering secondary messenger pathways as suggested by several workers (Haug, 1984, Taylor, 1988, Haug et al., 1994).

The importance of apoplast as site of activity of Al is further proved by X-ray microanalyis and secondary ion mass spectroanalysis studies, which indicate that a significant fraction of Al in roots is associated with apoplastic binding sites, predominantly in walls of cells of the root periphery (Vazquez et al., 1999). Since the net negative charge of the cell wall determines its cation exchange capacity (CEC). Consequently it determines the degree to which Al interacts with the cell wall. Tabuchi and Matsumoto (2001) reported that Al interactions lead to the displacement of other cations (e.g., Ca\(^{2+}\)) fundamental for cell-wall stability. As an outcome of this, the strong and rapid binding of Al alters cell wall structural and mechanical properties, making it more rigid, leading to a decrease in the mechanical extensibility of the cell wall which is required for normal cell expansion. Kinraide et al., (1998) reported that Al\(^{3+}\) interacts very strongly with the negatively charged plasma-membrane surface. Since Al has a more than 500-fold greater affinity for the choline head of Phosphatidylycholine (a-lipid constituent of the plasma membrane), than other cations such as Ca\(^{2+}\) have, Al\(^{3+}\) can displace other cations that may form bridges between the phospholipid head groups of the membrane bilayer. The result is the altered phospholipid packing and fluidity of the membrane. Besides, interaction of Al with the plasma membrane leads to screening and neutralization of the charges at the surface of the plasma membrane. This can alter the activities of ions near the plasma-membrane surface. In conclusion, the interactions of Al at the plasma membrane can modify the structure of the plasma membrane as well as the ionic environment near the surface of the cell; both can lead to disturbances of ion-transport processes, which ultimately perturb cellular homeostasis. Another measure of Al toxicity is the callose accumulation in the apoplast, which is an early symptom of Al toxicity (Massot et al., 1999). Callose synthesis depends on the presence of Ca\(^{2+}\), hence, it is argued that displacement of Ca\(^{2+}\) by Al from the membrane surface increases the pool of Ca\(^{2+}\) in the apoplast, which is required to stimulate the synthesis of callose. Sivaguru et al., (2000) reported that under Al stress, callose accumulation aggravates cellular damage by inhibiting intercellular transport through plasmodesma connections. Thus Al has many effects at the apoplast and symplasm levels that disturb the normal physiology the cell and functioning of the cell membrane and cell wall. These result in reduced plant growth and development, and ultimately reduced yield of crop plants.

**Conclusion**

With the decrease in pH of arable soils worldwide, due to indiscriminate use of fertilizers, the problem of Al toxicity in plants is likely to increase, and become a major limiting factor worldwide, more so in the developing countries. Since short term exposure to Al also are causing noticeable changes in the root apical meristem, the understanding of the mechanisms of Al toxicity in different plant species are important for reducing the toxicity symptoms in the plants of agronomic importance. Easiest solution to this problem is reducing the pace of acidifying the soil, which could in part be done reducing the dependence of chemical fertilizers.
REFERENCES