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# Leaching Losses of Micronutrient: A review

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**ABSTRACT: It is a well-established fact that for sustainable crop production, micronutrients are equally important as macronutrients. There are emerging though scattered evidences of crop productivity limitations by micronutrients as the addition of such nutrients is also limited. With the increasing agricultural intensification using high yielding cultivars, synthetic fertilizers; the exploitation rate of micronutrients has overtaken the rate of their replenishment. Leaching losses of such nutrients is a major constraint beside other factors. So, it is important to assess and quantify the leaching losses of such nutrients for sustainable crop production besides planning management strategies. The reduced availability of organic manures and more reliance on synthetic fertilizers is causing increased deficiencies of micronutrients because these fertilizers are highly nutrient specific. The over dependence on synthetic fertilizers has brought many ill effects including soil and environmental pollution through leaching etc. Majority of the studies were restricted to the dynamics and leaching behavior of macronutrients and micronutrients remained out of the scene though these nutrients are equally prone to leaching. The scientific evidences suggest that nitrate and sulphur possess similar leaching behaviour and phosphorus is least mobile. Potassium is less prone to leaching than calcium and magnesium. Among micronutrients, though very little and scattered scientific literature is available but it has been advocated that boron has the highest leaching potential and copper has the least. Therefore, equal attention should be paid to assess the leaching losses of micronutrients so that right micronutrient management technology could be generated encompassing the latest advancements in fertilizer formulations coupled with best management practices in order to get best use efficiency and sustaining/improving the overall environmental quality.**

**Keywords:** Leaching, macronutrients, micronutrients, management strategies.

## INTRODUCTION

The downward movement of dissolved nutrients with percolating water beyond the root zone in soil profile is nutrient leaching. The prerequisite for leaching to take place demand that the water content should exceed the field capacity with positive water balance which means the water input through rainfall and/or irrigation must exceed evapotranspiration. Therefore, leaching losses in general are higher under humid conditions (Havlin *et al.* 1999). The leached nutrients are temporarily lost from the system however, they can be recycled by growing deep rooted crops. The leached nutrients are a major contributor to groundwater contamination especially in intensively cultivated areas. Natural leaching occurs in humid conditions but agricultural activities contribute significantly in increasing the leaching irrespective of the climatic conditions (Havlin *et al.* 1999). Majority of the nutrients are prone to leaching depending on application, mobility and concentration in soil.

The significance of micronutrients in crop production is well documented. The increasing agricultural intensification with high yielding cultivars is exploiting the micronutrients more than their replenishment resulting in increased deficiency of majority of them thereby negatively impacting the crop productivity. Therefore, micronutrients need to be equally treated as macronutrients for sustainable crop production and maintaining/improving soil health under squeezing availability of organic manures. Earlier organics were considered to be the main source of micronutrients and presently used high analysis fertilizers are nutrient specific devoid of any impurity. Balanced application of essential nutrients is need of the hour for boosting agricultural production because they nourish the crops and enhance/sustain soil productivity. However, such nutrients are at risk of being lost in different ways (e.g., leaching, run-off, emissions) if not taken up by plants thereby increasing unnecessary costs of the farming business. Optimizing the right time and amount matching the crop need can have a positive impact on the soil health, environment, human health besides economic gain.

Majority of the work done so far has focused on soil incubation studies restricted to the dynamics and leaching behavior of macronutrients, mainly nitrogen and phosphorus may be because of their extensive use. It is well documented that maximum micronutrients are mobile in soil and are liable to leaching, even then their leaching losses have been least studied. There is emerging though scattered evidence of crop productivity limitations by micronutrients. Therefore, more research efforts are needed to understand adsorption and release process of micronutrients under different soil conditions. Amalal *et al.,* (2001) advocated that leaching losses of such nutrients is a major constraint beside other factors. Drainage water from the soils of the plains of North-western Pakistan was found to contain 1.39 to 9.79 times higher micronutrients as compared to the applied inputs in the form of fertilizers and irrigation methods (Gul *et al*., 2013). This means that the reserve of micronutrients in the soil is getting depleted at an alarming rate and would turn the fertile soils into the dust making them useless.

The critical range of micronutrients in plants and soils is very narrow so we need to make sure that they are being applied at the right rate to avoid any toxicity or deficiency in the plants. The low nutrient use efficiency is also a cause of concern for micronutrients. So, along with their mobility and leachability, it is important to study their movement and vertical distribution in the soil for which use of soil columns is a better, easy and cheap option. Soil type affects the leachability, mobility and distribution of micronutrients (Alvarez *et al.,* 2001). Use of laboratory scale soil columns is a simple, quick and affordable method to obtain leachates (Costa *et al*., 2020). Such studies will form the basis for micronutrient use guidelines based on 4R principles which include their right source, right rate, right place and right time of application. This article synthesizes the work done on assessment of leaching losses of macro and micronutrients.

**Factors affecting nutrient leaching:** Higher rainfall and/or irrigation exceeding the field capacity may cause more leaching (Schroth and Sinclair, 2003). However, in *Vertisols* at the onset of monsoon water infiltrates through macropores though bulk soil remains dry (Smaling and Bouma, 2007). Under such conditions, there is increased leaching through macropores when fertilizers are applied because there is little contact with soil matrix. Conversely, the macropores also retard the leaching by rapidly draining the surplus water (Cameron and Haynes, 1986; van Noordwijk *et al.,* 1991b). Sandy soils having high infiltration rate, low nutrient retention capacity and ferralitic soils having low organic matter content and low activity clays are more susceptible to leaching (von Uexkull, 1986a). Restricted rooting depth owing to subsoil acidity increases leaching whereas some nutrients easily get leached from organic soils (Schroth and Sinclair, 2003). An increased net positive charge of subsoil in many tropical soils decreases the mobility of nitrate and anions which may be taken up by deep rooted crops.

**General susceptibility of nutrients to leaching:** Mobility of a nutrient in the soil increases the leaching risk. Owing to more mobility in soil and least interaction with negatively charged soil matrix, nitrate is easily leachable (Robertson, 1989; Schroth *et al*., 1999a). As a result, in agricultural soils one may expect negative nitrogen balances because of leaching (Smaling *et al.,* 1993). Nitrate is also susceptible to leaching under seasonal climates owing to mineralization of organic nitrogen releasing large quantities of nitrates in the top soil (Birch, 1964). This process is often observed when a dry soil is rewetted by any means. The mineralization flush after rewetting the dry soil is also true for sulphur (Havlin *et al.,* 1999). In general, sulphate is easily leached from surface soils but the soils dominated by monovalent cations (K, Na) are more susceptible whereas, the soils having higher aluminum content show least sulphate leaching (Havlin *et al.,* 1999). Conversely, because of immobility, precipitation and adsorption on mineral surfaces, phosphorus is least leachable except in sandy and organic soils (Wild, 1988). The mobility of dissolved organic phosphorus forms in soil is higher than phosphate (Havlin *et al.,* 1999). Phosphorus may be lost in runoff water with eroded soil.

The percolating soil solution must be electrically neutral in order to carry the nutrients down the soil profile suggesting that an equivalent amount of cations is also leached with anions (Schroth and Sinclair, 2003). In most of the soils, calcium and magnesium are the most susceptible to leaching (Pieri, 1989). In sandy soils, with the application of potassium chloride or potassium sulphate, a significant amount of magnesium is leached (Havlin *et al.,* 1999). Calcium and magnesium possess higher leaching potential than potassium even when applied as fertilizers (Pieri, 1989). However, in high rainfall areas, sandy and organic soils, significant losses of potassium may occur (Malavolta, 1985; Havlin *et al.* 1999). Less information is available for micronutrients; however, in certain soils manganese and boron are susceptible to leaching (Havlin *et al.* 1999).

**Macronutrients as the main focus - some scientific evidences:** Most of the workers while studying the leaching losses of soil nutrients kept macronutrients as main focus owing to their extensive use in agriculture and contribution in causing environmental pollution. The average leaching losses of nitrogen and phosphorus have been extensively studied but such literature is not available for micronutrients. The mean leaching losses of nitrogen, potassium, calcium and magnesium from the soil in 11 months were 5, 13, 320 and 80 kg $ha^{-1}$

respectively (Oliveira *et al.*, 2002). The average leaching of potassium per year ranged from 3.64 to 22.7 kg $ha^{-1}$ (Gerzabek, 1996).

Effects of soil type on leaching of nitrate are highly significant. Leaching of ammonium ions in calcareous soils showed positive correlation with silt and clay content and the pH of the soil (Zarebi *et al*., 2012). However, leaching of nitrogen under split application of fertilizers was found to be several times lower than under lumped fertilization. Grouped quartiles of N leaching fraction computed for (a) sand and (b) Andosol in Model A (top) and Model B (bottom) (Fig 1). Scenarios represent lumped (S-1, A-1), two-split (S-2, A-2), three-split (S-3, A-3), and six-split (S-6, A-6) applications (Nakamura *et al.,* 2004).

Soil carbon plays a crucial role in determining the nitrate leaching. The study carried out by Kanthle *et al.,* (2018) has proved that decline in levels of soil carbon significantly enhanced nitrate leaching. Biochar has a mitigating effect on the leaching of nitrate nitrogen (Kanthle *et al.,* 2018). Soil amended with biochar had reduced mean cumulative leaching of total organic carbon by 30%, nitrate by 33% and nitrite by 34% (Mukherjee *et al.,* 2014). Nitrate leaching could be reduced by 29% in the carbon limiting soil with the application of biochar at the rate of 20 g $kg^{-1}$ of soil (Kanthle *et al.,* 2016). $N_2O$ emissions and inorganic nitrogen leaching can be mitigated by the application of biochar depending on the type of biochar, its age and soil type. Leaching of nitrate ions into ground water increased with increase in water application rate and nitrate concentration (Darby *et al.,* 2006). The diagram also depict that the nitrate is deposited at higher depth (~35 cm) with the maximum flux of 0.0442 cm $min^{-1}$.

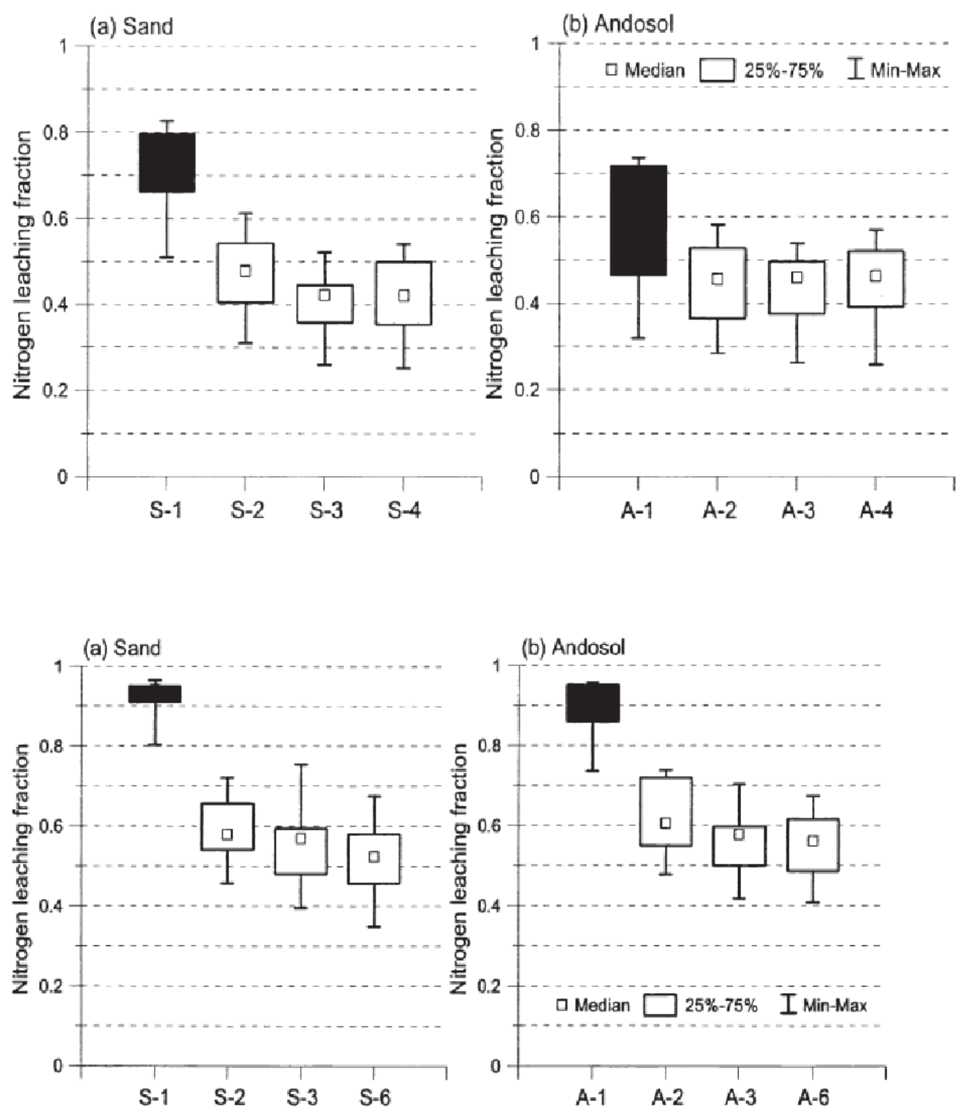


**Fig. 1.** Grouped quartiles of N leaching fraction computed from nine samples (1992–2000) for (a) sand and (b) Andosol in Model A (top) and Model B (bottom). Adapted from Nakamura *et al.,* (2004).

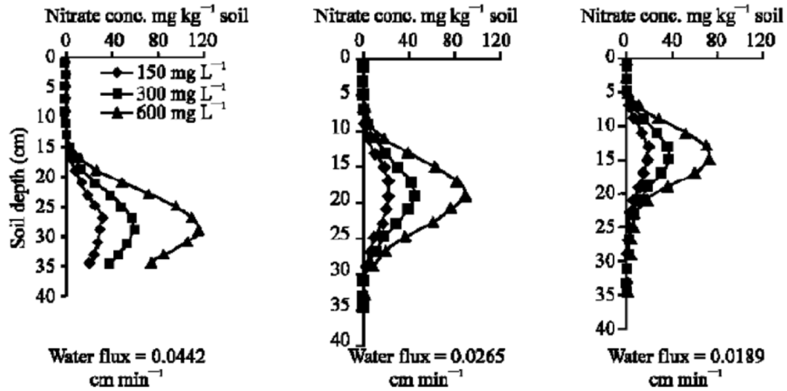


**Fig. 2.** Nitrate distribution profile at different nitrate concentrations and water application rates (Adapted from: Darby *et al.,* 2006).

**Table 1: Estimated single and annual P leaching intensity (LI) for the two types of soils.**

| Silt loam (kg P ha$^{-1}$) | | | Loam (kg P ha$^{-1}$) | | |
|---|---|---|---|---|---|
| Soil Olsen-P (mg P kg$^{-1}$) | Single event (50 mm) | Annual (600 mm) | Soil Olsen-P (mg P kg$^{-1}$) | Single event (50 mm) | Annual (600 mm) |
| 6.6 | 0.010.00[a] | 0.130.02[a] | 13.2 | 0.020.00[a] | 0.180.06[a] |
| 12.9 | 0.080.02[a] | 0.910.02[a] | 19.4 | 0.040.00[a] | 0.500.01[a] |
| 20.4 | 0.180.01[a] | 2.120.09[a] | 27.6 | 0.120.03[b] | 1.400.31[b] |
| 26.2 | 0.320.00[ab] | 3.850.03[ab] | 32.7 | 0.140.00[b] | 1.720.04[b] |
| 31.7 | 0.620.02[b] | 7.410.19[b] | 37.9 | 0.230.00[c] | 2.720.04[c] |
| 41.1 | 1.540.32[c] | 18.53.86[c] | 45.7 | 0.330.01[d] | 3.980.09[d] |
| 62 | 1.980.14[d] | 23.71.69[d] | 66.3 | 0.690.03[e] | 8.330.37[e] |
| 104 | 4.760.23[e] | 57.12.73[e] | 83.2 | 2.490.10[f] | 29.91.18[f] |
| 156 | 5.890.53[f] | 70.76.38[f] | 108 | 4.060.07[g] | 48.40.71[g] |

The rainfall infiltration amounts used for LI estimation of DRP are 50 mm for single infiltration events and 600 mm for annual values, respectively. The early value of DRP was used in the calculation of LI. a–g Data signed by the same letter in the same column indicates that their differences are not significant at p¼ 0.05 level. (Adapted from: Li *et al.,* 2013).

Inceptisols have higher phosphorus leaching potential and soil texture and P-sorption capacity of soils are important factors that affect leaching losses (Rashmi *et al.,* 2017). A column study revealed that shortening of water logging time can reduce leaching risk of phosphorus and it was more severe in coarse textured soils as compared to fine textured soils (Li *et al.* 2013).
The findings of Azevedo *et al.,* (2018) have demonstrated that phosphorus mobility depends on the concentration of the soluble phosphorus in the soil, however, the presence of Fe & Al oxides reduces the mobility of P in sandy soils. Maximum fertilizer recommendation studies are focused on macronutrients. Fertilizer solubility influenced leaching losses of phosphorus in the short term (<1 year), however, the water and citrate insoluble phosphorus fertilizers also contribute to phosphorus leaching in the long run Weaver *et al.*, 1988). Kui *et al.,* (2008) have highlighted that vertical migration of phosphorus is soil property dependent. After four leachings, there was maximum reduction in K content from soil column in case of sandy soils while minor decrease was observed in clay loam (Sharma and Sharma, 2011). Leaching of potassium in the soil column was affected by the irrigation depth. Increase in the irrigation depth increased the leaching of potassium ions and 3.26% and 43.91% of the applied K was lost from clayey and sandy soils respectively when water replacement percentage was 150% and the losses increased to 7.99 and 57.04% from clayey and sandy soils respectively when water replacement percentage was 200%. This indicated that more leaching losses from coarse textured soils (Mendes *et al.,* 2016).

**Table 2: Cumulative amount of potassium (mg) leached along 81 days in undisturbed columns of clayey and sandy soils, as a function of different irrigation depths.**

| Time (days) | Soil | Water replacement percentage | | | |
|---|---|---|---|---|---|
| | | 50% [(1)] | 100% | 150% | 200% |
| 81 | Clayey | 0.00 a [(2)] | 0.37 a | 10.20 b | 25.00 b |
| 81 | Sandy | 0.00 a | 9.73 a | 137.43 a | 178.53 |

[(1)]50, 100, 150 and 200% represent the % of water applied through irrigation based on the difference of mass of the column irrigated at 100%; [(2)]Means followed by the same letter, in the column, do not differ by Turkey test at 0.05 probability level; F Test = 241; CV = 17.54%; LSD = 13.84. Adapted from Mendes *et al.,* (2016).

Moreover, the remediation measures to control leaching losses were also worked out by keeping macronutrients as the main focus. In a batch and column experiment on N and P leaching, it was observed that natural zeolite mixed with swine manure could be a good option to retard excess leaching of nutrients in the soil (Colombani *et al.,* 2015). Leaching studies of N, P, Mg, Si indicated that biochar addition could be a better management option to retard excess leaching of nutrients in the soil (Laird *et al.,* 2010). By reducing soil phosphorus accumulation along with shortening of water logging time can help in mitigating P leaching risk (Li *et al.,* 2013). Establishment of maize buffer strips on a soil with low hydraulic conductivity, would help in mitigating solute drainage (Heliwell, 2011).

**Micronutrient leaching studies- some scientific evidences:** There are some but scattered evidences of micronutrient leaching studies in India. However, many workers have investigated micronutrient leaching elsewhere long back. As regards soil fertilization, micronutrient amendments exhibit little movement in the soil profile. Even in sandy soils, applied Zn showed very little movement (Scharrer and Hofner, 1958). The study conducted by Lundblad *et al*., (1949) demonstrated that addition of Cu as high as 250 kg $ha^{-1}$ to peat registered less than 0.2 per cent movement beyond top 5 cm soil depth. Even after 11 years, Co applied to a coarse textured soil in New Zealand did not show any movement out of surface soil as reported in an unpublished data by U.S. Plant, Soil and Nutrition Lab., Alban. Among the micronutrients, irrespective of the conditions, Cu probably exhibits least mobility. The relative movement of Cu, Zn and Mn in pineapple soils was studied by Reuther *et al*., (1952) which demonstrated that these elements get immobilized in the given order. Whereas Miyamoto *et al*., (2013) reported that micronutrient leaching follows the order Mn>Zn>Fe>Cu. Soil types and stability of the chelates used affects the mobility, distribution and leachability of Zn in soil columns. Less mobile and moderately stable Zn sources act as a stock of micronutrients (Alvarez *et al*., 2001). A comparative study on relative mobility of different zinc sources by Gangloff *et al.,* (2006) concluded that Zn-EDTA, ZnLigno & $ZnSO_4$ were most mobile Zn sources; ZnOx55 was less mobile while ZnOx26 & ZnSuc were immobile. To arrest the leaching losses of Cu & Zn, a metallurgy waste contaminated soil layer over the uncontaminated soil in the soil columns act as an effective barrier to the mobilization of metals and to minimize their leaching (Rodella *et al.,* 2009).

But boron is an exception to the above findings. In a podzol, after a few days leaching with water 64 to 76% of B is lost (Katalymov, 1952) whereas, the loss was to the tune of 30 to 52% from a chernozem. It is by no means an isolated one but an extreme example. Within 6 months, B added in herbicidal amounts in a sandy loam soil is lost from the top 8 inches (Winsor, 1952). The high pH and high clay content significantly reduce B movement in soil profiles (Scharrer and Hofner, 1958). Kubota *et al*., (1948) explained that when B in excess (toxic) to most of the plants it gets leached quite rapidly from the majority of the soils but when it is present in small amounts, the leaching becomes sluggish even though more sensitive crops may still exhibit toxicity symptoms. In a column experiment boron leaching was found greater from soil treated with borax as compared to the soil treated with calemonite (Saleem *et al.* 2011). Leaching of boron decreased with increase in soil pH (Sá and Ernani, 2016).

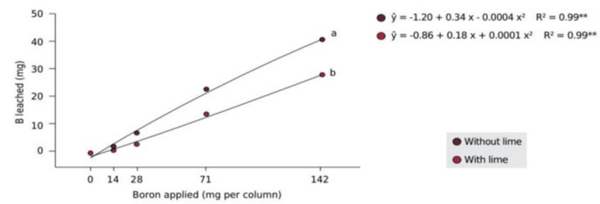


**Fig. 3.** Total amount of boron leached after 15 percolations with distilled water as affected by liming and rates of boron applied. Average of three replications. Regression curves followed by different letters differ by the F-test at the 5% significance level. ** significant at 1%. Adapted from Sá and Ernani (2016).

Drainage water from the soils of Northwestern Plains of Pakistan contained 1.39 to 9.79 times higher micronutrients as compared to applied inputs in the form of fertilizers and irrigation water (Gul *et al.* 2013). The right source and right time of application of micronutrients need to be standardized and popularized. The study carried out by Miyamoto *et al.,* (2013) argued that performance of micronutrient fertilizers is better when applied in dry conditions because small amounts of micronutrients were extracted from the soil under flooded conditions. The factors that affect leaching of micronutrients could be different or same as that of macronutrients but need to be verified under diverse situations and to do so soil column experiments may be a better option. The results of the study by Sharma *et al.,* (2009) demonstrated two things. First, Zn, Fe & Mn content in salt affected soils of Punjab was higher in soils with fine texture as compared to coarse texture and second the content increased with increasing organic carbon but decreased with increase in pH and calcium carbonate content. Conversely leaching losses of boron decreases as the pH of the soil increases (Sa and Ernani, 2016). The Lyallpur soil having higher clay content adsorbed greater amounts of B and Zn as compared to the Sultanpur soil. However, the solute velocity in Lyallpur soil columns was lower than that of the Sultanpur soil series mainly because the movement of the solute was attributed to high dispersion (Hassan *et al.* 2008). After the application of urea, mobilization of metal-organic complexes in the soil was a reason of leaching of Cu & Fe while Mn & Zn leaching occurred due to increased soil acidity caused by nitrification (Boateng and Ballard, 1981). There was a drastic decrease in the copper concentration from top layer to the bottom layer of the soil. Solutions at pH 7 & 9 leached out less copper and at pH 1, 3 & 11 copper mobility was enhanced (Xu *et al.,* 2005).

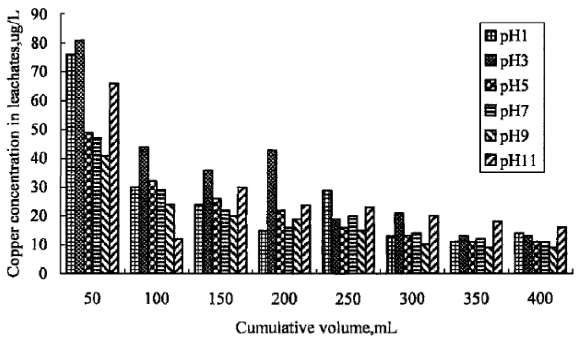


**Fig. 4.** Copper leaching varied with the changing pH. Adapted from Xu *et al.,* (2005).

Kinetic factors influence copper leaching in soil columns. Leaching with pH 5, 0.01M NaOAc resulted in copper leaching due to displacement of exchangeable $Cu^{2+}$ by $Na^{+}$. When DOC solution of pH 7 and 135mg/L was used, it also caused leaching of specifically sorbed Cu substantially due to Cu–DOC complex formation (Burton *et al.,* 2005).

**Possible ways to reduce leaching losses:** Leaching and overfertilization of microelements are the limitations of traditional fertilizers. As precision agriculture is trending now-a-days, low solubility fertilizers, coated fertilizers, biobased and nanofertilizers could remove these limitations (Mikula *et al.,* 2019). Adoption of such agricultural practices which increase the synchrony and synlocation of nutrient uptake with nutrient supply from soil, organics or synthetic fertilizers can reduce/minimize the nutrient losses through leaching. These include:

**1. *Fertilizer nanotechnology:*** Nanostructured formulations have the capacity to control the leaking or leaching of fertilizer nutrients (Cui *et al.* 2010). Use of nanofertilizers increased the nutrient use efficiency (Manjunatha *et al.,* 2019). In a soil column experiment, 78% P was found to be recovered in the leachate from the Triple superphosphate (TSP) applied sand whereas, P recovery in the leachates from positively charged, negatively charged and neutral hydroxyapatite nanoparticles was low (0.5%) for all treatments of sand, *Ultisols* and *Vertisols* (Xiong *et al.* 2018). Application of neem, resin, nano-rock phosphate and nano-ZnO coated urea reduced nitrate leaching in a *Vertisol* by 18.3, 28, 25.7 and 35.1% respectively (Jadon *et al.* 2018).

**2. *Slow release fertilizers:*** Ammonium sulphate loaded into Clinoptilolite zeolite increased nitrogen utilization in crops and minimized nitrogen leaching (Perrin *et al.* 1998). Surfactant modified zeolite when used as fertilizer additive significantly reduced the leaching of sulphates from the soil (Li and Zhang, 2010). Urea when granulated after blending with brown coal, significantly decreased leaching and volatilization losses of nitrogen and increased the retention of nitrogen fertilizers in the soil (Saha *et al.,* 2018).

**3. *Soil amendments:*** Calcium chloride or calcium chloride + calcium carbonate when used as amendment in sandy soils reduced the leaching losses of N, K, Mg & Cu. These amendments can be a part of best management practices for sandy soil regions (Yang *et al.* 2007). In a batch and column experiment on N and P leaching, natural zeolite mixed with swine manure was found a good option to retard excess leaching of nutrients in the soil (Colombani *et al.,* 2015). Leaching studies of N, P, Mg, Si has proved that biochar addition could be a better management option to retard excess leaching of nutrients in the soil (Laird *et al.,* 2010).

**4. *Sowing time:*** Sowing before onset of rainy season to utilize the mineralization flush of nitrogen upon soil rewetting (*Myers et al., 1994*).

**5. *Establishment of vegetative cover:*** To avoid leaching losses from bare soil, establish the vegetative cover quickly (Webster and Wilson, 1980; von Uexbull, 1986b).

**6. *Split application*:** Application of fertilizer (especially nitrogen) in many splits rather once during the cropping period.

**7. *Fertilizer placement:*** Placement of fertilizers in the zone of maximum root activity (IAEA, 1975; Havlin *et. al.,* 1999).

**8. *Foliar application:*** Foliar feeding of nutrients having higher leaching potential.

## SUMMARY AND CONCLUSIONS

The movement of nutrients with percolating water beyond the root zone in soil profile is nutrient leaching and requires a positive water balance. Therefore, humid regions exhibit higher leaching losses. Owing to leaching, the nutrients however, are temporarily lost from the system but by growing deep rooted crops these can be recycled. Agricultural intensification is significantly contributing to leaching deteriorating the soil, water and overall environmental quality. The leaching losses are governed by rate and time of fertilizer application, mobility and concentration in soil. The major nutrients (NPK) have been extensively studied in relation to leaching losses owing to their requirement in crop production and simultaneous contribution in environmental degradation. Nitrate and sulphur are more prone to leaching and phosphorus is immobile however, gets leached with runoff. Calcium and magnesium are leached more rapidly than potassium. Among micronutrients, very scattered information is available. Boron is an exceptional micronutrient having higher leaching potential and copper has the least. Therefore, more focus is needed to study the leaching losses and mobility of micronutrients in the soil under diversified climatic conditions. Future research needs to be focused on assessing the leaching losses of micronutrients addressing the 4R principles (right time, rate, source and timing) by including the new advancements in fertilizer industry such as slow release fertilizers, nanofertilizers, use of soil amendments, foliar application etc.

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