Knowledge of zinc (Zn) distribution among various fractions will help to predict the potential of the soil to supply sufficient Zn for crop production. The present study was done to investigate Zn fractions, Zn availability factor (AF) and their relationship with soil properties of Zn-deficient tropical paddy soils. The samples of two soil orders (six soil series) were sequentially extracted with chemical extractants in two different growth stages of rice (maximum tillering and flowering stages). The proportion of Zn fractions extracted at the maximum tillering stage followed the order, water soluble plus exchangeable (WE) < crystalline sesquioxide (Cry) < manganese oxide (MN) < organically bound (Org) < amorphous sesquioxide (Amor) < residual Zn (Res), whereas the order at the flowering stage was as follows: WE < Mn < Cry < Org < Amor < Res. Cation exchange capacity (CEC), clay content and organic carbon (OC) were the most important factors controlling the distribution of Zn in soils. The AF was low in Tok Young (1.79%), high in Telomlog (17%) and medium in the rest of soil series (around 8%). A stepwise multiple linear regression and principal component analyses showed that OC, clay content and CEC were the main variables that explained the predictability of Zn fractions. The result of the length of submerging showed that the WE, Org and Cry concentrations decreased, while Amor, MN, and the sum of all Zn fractions increased with increase in the flooding period. The extractability and solid-phase fractionation of Zn in two different times of soil sampling showed the importance of timing of Zn fertilizer application and flooding or pre-flooding in Zn availability.

**Keywords:** tropical paddy soils; zinc fractions; soil properties

**Introduction**

Zinc deficiency is the most common nutritional disorder of Asia’s rice paddy fields immediately after N and P constraints.[1] Zinc availability is reported to be associated with its transformation in soils and plant continuum through various mechanisms, such as adsorption by clay surfaces, hydrous oxide minerals, organic matter and so forth, which affect crop Zn uptake. Thus, understanding the distribution of Zn among various fractions of soils will help to characterize the chemistry of Zn in soils and possibly its availability for plant uptake.

Zinc availability to rice is strongly related to Zn fractions in the soil.[2] The soil Zn fractions are highly dependent on the physicochemical soil properties, such as pH, organic carbon (OC), clay content and cation exchange capacity (CEC).[3,4] Paddy fields with different soil moisture regimes bring about numerous changes in the soil physicochemical and electrochemical properties, such as pH, Eh, electrical conductivity (EC), CaCO₃ content and amorphous and crystalline oxides of Fe and Mn. Thus, the chemistry and effect of the aforementioned properties appear to be of major importance in Zn fractions, and therefore improve the available Zn pools.[5] The distribution of Zn fractions among soil particles is vital to supply adequate amounts of Zn needed for crop growth.[6,7] The most important forms of Zn are water extractable (WE), organically bound (Org), amorphous sesquioxide (Amor), crystalline sesquioxide (Cry), manganese oxide (MN) and residual (Res),[8] while the WE and Org are the phyto-available forms of Zn for crop growth.[9]

Sequential selective extraction procedures are commonly used to understand and predict bioavailability, leaching, transformation and chemical forms of nutrients in agricultural soils. Sequential extraction procedures start with a weak reagent, followed by a stronger one to more aggressive chemical solvents.[10] Several sequential extraction schemes have been reported in the literature.[8,11–14] Despite many researches on Zn fractionation in paddy soils, there have been few studies conducted to fractionate soil Zn in Zn-deficient tropical paddy fields. Thus, the current study was undertaken to determine Zn fractions, Zn availability factors and their relationship with some important soil properties of Zn-deficient tropical paddy soils.

**Materials and methods**

The laboratory incubation experiment was conducted on two tropical soil orders (Ultisols and Entisols) that had been divided into six soil series. Available Zn concentrations in all selected soils were below than the critical
level of Zn (double acid method). The six soil series were sampled from the surface layer (0–30 cm) of rice paddy fields in Kelantan and Kedah states, Malaysia. The selected soils were classified according to American Soil Taxonomy procedure. The soil samples were air-dried, ground and passed through a 2-mm metal sieve and stored for the current experiment. The physical and chemical properties of the selected soil samples were determined, such as texture, OC, pH, CEC, available Zn, Fe²⁺ and Mn²⁺. A pipette method was used to determine the soil particle-size.[15] A 1.25 (weight: volume) soil to water suspension was used to determine the pH of the soil. The oxidizable organic matter was measured using the Walkley–Black wet oxidation method, where organic matter content of the fine soil particle was oxidized by chromic acid making use of the heat of sulphuric acid.[16] The soil EC was determined in a 1:2 (w:v) soil to water suspension. The CEC and basic cation concentration were measured by leaching, replacing and titration procedures [17] and determined by the atomic absorption spectrophotometer (AAS). Acidic cations were measured by double acid method (extracted with a mixture of 0.05 N HCl and 0.025 N H₂SO₄).[18]

The selected soil samples were incubated for 60 days in submerged condition such as paddy field (5 ± 0.5 cm standing water) and Zn fractions were measured at 30 (maximum tillering stage) and 60 (flowering stage) days after the periods of submerging. The Zn fractionations (fertility fractions) were determined using a modified sequential extraction procedure of Murthy [19] proposed by Mandal et al. [11]. The Zn pools in soils were divided into seven fractions (Table 1). Zn forms in soils, except in steps 6 and 7, were extracted from soils using 50 mL plastic centrifuge tubes with individual extracting solutions (see Table 1) and shaken in a rotary shaker at room temperature (25 ± 2 °C). The supernatant solutions obtained from each successive stage of extraction were centrifuged at 3,500 rpm for 15 min, decanted and filtered with Whatman No. 42 filter paper. It was absolutely crucial to prevent any delay between adding the extraction solutions and starting shaking them. Three replicates of incubation, all sequential extractions and analyses were performed for each soil sample. The concentration of Zn was determined using a Perkin Elmer 400 AAS with detection limit of 6 × 10⁻³ mg L⁻¹. The 1000 mg L⁻¹ Merk Zn standard solutions were used to prepare Zn standard solutions in background solvents. The accuracy of Zn concentration was controlled using reference material certified for extractable element content and species by the Community Bureau of Reference. Quality control was evaluated by 20 sample intervals and using the best-fit model of the calibration curve with less than ±10% variation. The correlation and regression analyses were performed using SPSS software package (IBM version 22.1). The correlation coefficients were used to explore the relationship between variables. Multiple regressions were used to find out the effect of independent variables on dependent variables. The step-wise regression method was used to calculate the most contributing factors among the dependent variables.

Results

Soil classification and characteristics

Three types of soils were classified as Entisols and the other three soils considered as Ultisols divided into four great soil groups with recent marine alluvial geological

| Fractions | Solution (ml) | Soil (g):solution (ml) | Conditions | References |
|-----------|--------------|------------------------|------------|-----------|
| (1) Water soluble + exchangeable (WE) | IM (NH₄)OAc (pH 7.0) | 5:20 | Shake 1 h | Murthy [19] modified by Mandal & Mandal [31] |
| (2) Organically complexed (Org) | 0.05 M Cu(OAc)₂ | 5:20 | Shake 1 h | Murthy [19] modified by Mandal & Mandal [31] |
| (3) Amorphous sesquioxide bound (Amor) | 0.2 M (NH₄)₂C₂O₄·H₂O + 0.2 M H₂C₂O₄ (pH 3.0) | 5:20 | Shake 1 h | Murthy [19] modified by Mandal & Mandal [31] |
| (4) Crystalline sesquioxide (Cry) | 0.3 sodium citrate + 1.0 M NaHCO₃ + 1 g Na₂S₂O₃, [citrate-bicarbonate-dithionite (CBD)] | 5:20 | Boiling water bath, 10 min, stir occasionally, keep on water bath, (70–80 °C), 15 min, stir occasionally | Murthy [19] modified by Mandal & Mandal [31] |
| (5) Manganese oxide (Mn) | 0.1 M NH₂OH·HCl (pH 2.0) | 5:50 | Shake 30 min | Chao [34] |
| (6) Residual (Res)* | HCl + HNO₃ conc. | 1:08 | Aqua regia | Aqua regia |
| (7) Total | HCl + HNO₃ conc. | 1:08 | Aqua regia | Aqua regia |

*Samples of step 6 dried and finely grounded.
Zinc fractions

The results of sequential fractionation after 30 and 60 days of submerging (Table 4) showed low to medium levels of the total Zn (10.14–52.02 mg kg⁻¹). The residual fractions as the largest part of total Zn ranged from 54 to 82%, whereas the WE as the smallest portion varied between 1.25 and 3.45% of the total Zn. The low bioavailability of Zn in all soil series stressed that the selected paddy soils were Zn deficient. The crystalline bound Zn ranged from 1.9 to 5.8%, followed by Mn (1.69–5.25%), Org (1.2–13.6%), Amor (6.1–18.7%) and Res (47.2–75.3%). Thus, a Duncan’s separation of averages established for 30 days samples: WE < Cry < Mn < Org < Amor < Res, whereas for 60 days were: WE < Mn < Cry < Org < Amor < Res.

Submerged duration effects on Zn fractions concentration

The incubation period with standing water had a significant effect on the Zn fractions. The WE, Org and Cry fractions decreased with increase in the periods of incubation under submerged condition, whereas the other fractions increased. The concentration of WE, Org and Cry fractions decreased from 0.72 at 30 days to 0.68 at 60 days, 0.66 to 0.63 and 1 to 0.8 mg kg⁻¹, but Amor, Mn and Res increased from 6.28 to 6.32, 1.19 to 1.32 and 38.7 to 39.1 mg kg⁻¹, respectively (Tables 4 and 5).

Availability factor and relative error

The water-soluble plus organically bound fractions were considered to be the most phyto-available forms of Zn for plant uptake.[9,20] These fractions were addressed as factors affecting the relative availability of Zn in the soils. Thus, the availability factor (AF) could be determined by Equation (1):

\[
AF = \left( \frac{WE + Org}{Total} \right) \times 100
\]  

The AF values were low for Zn in slightly acidic Tok Young soil series (1.79%), much higher in neutral Tele-mong series (17%) and medium in the other soil series (around 8%). The AF for Zn generally gave the value of 8.80% (on average).

To quantify the differences between the total Zn and the sum of fractions (SUMF) concentration that extracted separately, a descriptive analysis (relative error) (Equation (2)) was performed. Relative error gives an indication of how good a measurement is relative to the size of the thing being measured. The relative error is the absolute error divided by the exact value. In case of metal fractionation, it could be calculated according to Equation (2).

Relative error (RE%) = \left( \frac{SUMF - Total}{SUMF} \right) \times 100  

According to the results, except Chengai soil series, the RE varied from −4.5 to −8.5%, indicating that the total Zn contents were higher than the SUMF (Table 4). Compared to the total Zn determination, only a small but negligible amount of soils in the sequential extraction procedures was lost because of the filtration of the supernatant solution and/or the sorption to the wall of the centrifuge tube. Therefore, the weight of the extracted soil decreased during the extraction steps and caused little error in the measured Zn concentration. Thus, the SUMF was not equal to the total Zn concentration.

Zinc fractions and soil characters contributions

Correlation analysis indicated that there was a significant positive relationship between the WE and clay content (0.27**), CEC (0.44**) and OC (0.28**) at the 99% confidence level. In contrast, the Org fraction poorly correlated with pH (0.15*) at the 95% confidence level. Also a significant positive correlation was found between the Org and OC (0.43**), CEC (0.52**) and clay (0.38**). The pH of the soil had no significant correlation with any fractions, except the Org. The Amor fraction only significantly positively correlated with Ca (0.13*). Manganese oxide fraction had significant positive correlation with Clay (0.46**) then by CEC (0.35**), followed by soil Mn (0.34**) and OC (0.31**) fractions. The Cry fraction followed the same trend as the WE, but a few differences were found in its correlation coefficients (Table 7). Also, the Res and SUMF showed the same pattern in relationship with soil properties – positively and significantly correlated with clay (0.41**), whereas negatively and significantly correlated with EC (−0.40**). Also, the results showed a significant positive correlation between the total Zn and soil Mn (0.21**) and CEC (0.16**) (Table 6).

Table 2. Soil classification of selected soils.

| Soil series     | Great group | Parent material              |
|-----------------|-------------|------------------------------|
| Kundur          | Fluvaquent  | Marine, estuarine deposits   |
| Chengai         | Paleudult   | Marine, estuarine deposits   |
| Lubok Itek      | Fluvaquent  | Recent alluvium              |
| Tepus           | Kandiaquilt | Recent alluvium              |
| Telemong        | Udorthent   | Recent alluvium              |
| Tok Yang        | Paleudult   | Recent alluvium              |

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The water-soluble plus exchangeable fractions had highly significant positive correlation (0.73 **) with another phyto-available fraction (Org), followed by Cry (0.63 **) and the total Zn (0.21 **). The Org showed highly significant relationship with Cry (0.74 **), then with Amor (0.60 **) and SUMF (0.29 **) in contrast with WE fraction. There was a significant positive correlation between MN fraction and Cry (0.55 **) and Res (0.21 **). The Zn fractions showed high correlation with the Res fraction by increasing the strength of the extractant, whereas the Amor fraction was found to have high positive correlation with the Res (0.68 **). The total Zn highly correlated with the Res, the highest concentration fraction (0.94 **). The total Zn in two extreme ranges of pH was low Tepus as acid sulphate soil (pH 4) (10.51 mg kg\(^{-1}\)) and Telemong soil series as neutral soils (10.14 mg kg\(^{-1}\)) (pH 7). However, the other soils with a pH of around 5

### Table 3. Physicochemical properties of the selected soils.

| Soil series   | EC \(\times 10^{-6}\) (ds m\(^{-1}\)) | pH | OC (%) | CEC (cmolc kg\(^{-1}\)) | Ca (cmolc kg\(^{-1}\)) | Mg (cmolc kg\(^{-1}\)) | K (cmolc kg\(^{-1}\)) | Ava. Zn (mg Zn kg\(^{-1}\) soil) |
|---------------|----------------------------------|----|--------|------------------------|------------------------|------------------------|------------------------|-------------------------------|
| Lubok Itek    | 163                              | 5  | 4.44   | 16.43                  | 3.12                   | 0.06                   | 0.11                   | 1.05                          |
| Kundur        | 40                               | 5  | 5.46   | 2.63                   | 17.57                  | 3.43                   | 0.05                   | 0.01                          |
| Tok Yong      | 27                               | 5  | 5.43   | 1.38                   | 8.5                    | 2.15                   | 0.02                   | 0.004                         |
| Chengai       | 163                              | 5  | 5.26   | 1.73                   | 16.36                  | 3.51                   | 0.05                   | 0.002                         |
| Tepus         | 245                              | 7  | 1.93   | 2.85                   | 7.05                   | 0.68                   | 0.03                   | 0.001                         |
| Telemong      | 142.3                            | 7  | 1.73   | 6.40                   | 3.98                   | 0.06                   | 0.003                  | 1.19                          |

| Soil series   | Mn (meq 100 g\(^{-1}\) soil) | Fe | Clay | Silt (%) | Sand | Texture | Soil order |
|---------------|-------------------------------|----|------|----------|------|----------|------------|
| Lubok Itek    | 69.25                         | 569.7 | 84.9 | 12.23   | 2.79 | C        | Entisols   |
| Kundur        | 13.44                         | 1752 | 45    | 54.37   | 0.55 | Si·C     | Entisols   |
| Tok Yong      | 40.25                         | 665  | 38.7  | 48.8    | 12.38| Si·C·L   | Ultisols   |
| Chengai       | 68.5                          | 1050 | 44.6  | 47.42   | 7.81 | Si·C     | Ultisols   |
| Tepus         | 64                            | 19.95| 35.6  | 57.86   | 6.41 | Si·C·L   | Ultisols   |
| Telemong      | 12.75                         | 292.4| 16    | 28.17   | 55.73| Sa·L     | Entisols   |

### Table 4. Zinc fractions in the selected soils and the AF of soils.

| Soils         | WE (mg kg\(^{-1}\) soil) | Org (mg kg\(^{-1}\) soil) | Amor (mg kg\(^{-1}\) soil) | MN (mg kg\(^{-1}\) soil) | Cry (mg kg\(^{-1}\) soil) | Res (mg kg\(^{-1}\) soil) | SUMF (mg kg\(^{-1}\) soil) | Total (mg kg\(^{-1}\) soil) | Ava. ratio | Relative error (%) |
|---------------|--------------------------|--------------------------|---------------------------|--------------------------|--------------------------|--------------------------|---------------------------|---------------------------|-------------|-------------------|
| Tok Yong      | 0.72                     | 0.66                     | 6.28                      | 1.19                     | 1.00(0.26)               | 38.7                     | 47.649                    | 52.02                     | 0.48        | −8.5(−9.17)       |
| Lubok Itek    | 0.52                     | 3.04                     | 2.53                      | 0.94                     | 0.9                      | 31.3                     | 39.23                    | 41.56                     | 0.58        | −5.6(−5.95)       |
| Kundur        | 0.52                     | 1.48                     | 1.67                      | 0.42                     | 0.9                      | 11.7                     | 21                       | 24.78                     | 0.285       | 5(−5.24)          |
| Chengai       | 0.42                     | 1.15                     | 2.2                       | 0.95                     | 0.67                     | 9.03                     | 15.43                    | 18.05                     | 0.39        | −17(−20.92)       |
| Tepus         | 0.34                     | 0.58                     | 0.88                      | 0.24                     | 0.61                     | 7.37                     | 10.01                    | 10.51                     | 0.48        | −4.5(−4.94)       |
| Telemong      | 0.35                     | 1.38                     | 1.9                       | 0.38                     | 0.45                     | 5.17                     | 9.61                     | 10.14                     | 0.48        | −5.2(−5.43)       |

### Table 5. Simple correlation coefficients (r) for relationships between sequential extracted fractions (mg kg\(^{-1}\) of zinc.

| Zinc fractions | WE | Org | Amor | MN | Cry | Res | SUMF | Total |
|----------------|----|-----|------|----|-----|-----|------|-------|
| pH             | 0.04| 0.15*| 0.07 | 0.09| 0.04| 0.02| 0.05 | 0.05  |
| EC             | −0.22**| −0.09| −0.15*| 0.09| 0.09| −0.09| −0.40**| −0.40**| −0.42**|
| OC             | 0.28**| 0.43**| −0.04| 0.31**| 0.34**| 0.05| 0.13*| 0.04  |
| CEC            | 0.44**| 0.36**| 0.03| 0.35**| 0.50**| −0.005| 0.089| 0.16**|
| Ca             | 0.27**| 0.40**| 0.13*| 0.22**| 0.28**| −0.09| 0.01| 0.08  |
| Mg             | 0.27**| 0.52**| 0.05| 0.31**| 0.28**| −0.26**| −0.14**| −0.13**|
| Mn             | −0.19**| −0.11| 0.026| 0.34**| −0.02| 0.25**| 0.22**| 0.21**|
| Fe             | 0.422**| 0.21**| 0.03| 0.05| 0.37**| −0.09| −0.09| 0.08  |
| Clay           | 0.27**| 0.38**| 0.06| 0.46**| 0.38**| 0.41**| 0.41**| −0.42**|

*Significance at 0.05.  
**Significance at 0.01.
Table 6. Simple correlation coefficients (r) for relationships between sequential extracted fractions (mg kg\(^{-1}\)) of zinc.

| Fractions | WE  | Org | Amor | Mn  | Cry | Res | SUMF | Total |
|-----------|-----|-----|------|-----|-----|-----|------|-------|
| WE        | 1   | 0.74** | 0.37** | 0.39** | 0.63** | 0.05 | 0.17** | 0.21** |
| Org       | 1   | 0.60** | 0.58** | 0.74** | 0.74** | 0.02 | 0.29** | 0.26** |
| Amor      | 1   | 0.54** | 0.45** | 0.23** | 0.68** | 0.12 | 0.32** | 0.28** |
| Mn        | 1   | 0.55** | 0.21** | 0.41** | 0.28** | 0.05 | 0.28** | 0.20** |
| Cry       | 1   | -0.02 | 0.22** | 0.28** | 0.17** | 0.02 | 0.29** | 0.26** |
| Res       | 1   | 0.96** | 0.94** | 0.90** | 1      | 0.99**|      |       |
| SumF      | 1   |      |      |      |       |      |      |       |
| Total     |     | 1    |      |      |       |      |      |       |

*Significance at 0.05.
**Significance at 0.01.

The results of multiple linear regression (stepwise) analysis showed that the OC and CEC were the main variables that influenced the predictability of the most potentially extractable amount of Zn forms (Table 7). The best-fit models for the phyto-available Zn fractions and the total Zn with soil characters were:

\[ WE = 0.17 + 0.03CEC - 0.04\text{soil Mn} + 0.07OC \]  
\[ (R = 0.52) \]

\[ \text{Org} = -0.1 - 0.08\text{Mg} + 0.19OC \]  
\[ (R = 0.59) \]

\[ \text{Total Zn} = 0.90\text{Res} + 1.24\text{Amor} \]  
\[ (R = 0.81) \]

Based on Equations (1) and (2), the CEC was the dominant property in explaining the WE, whereas the OC was the most effective parameter for describing the behaviour of Org fraction. On the other hand, multiple linear regressions (stepwise) were performed to assess the relative and/or unique contributions of soil properties in the prediction of Zn AF in soils. The results indicated that OC and CEC were the main variables that influenced the predictability of the AF of Zn (Equation (3)).

\[ AF = 1.20 + 0.87OC - 0.02\text{soil Mn} + 0.07CEC \]  
\[ (R = 0.54) \]

To complete the study, a principal component analysis (PCA) was done which considered the concentration of Zn fractions as variables (Figure 1). According to this figure, the total Zn, SUMF and Res; Amor and MN; and WE, Org and Cry were fairly close together, indicating a close relationship among them. These findings could confirm the correlation results. Also, the PCA results for Zn fractions and the most important soil characters as variables indicated that OC and clay content were the most effective on the distribution of Zn fractions in the extracted soils. Furthermore, the pH of the soil appeared to be a non-effective factors, affecting the concentration of phyto-available Zn contents (WE and Org) (Figure 2). The correlation, regression and PCA analyses indicated that OC and clay content were the soil properties which were more related to the distribution of Zn forms in the selected tropical paddy soils.

**Discussion**

The available Zn (double acid) [18] contents of all soil series were lower than the critical limit of Zn concentrations in paddy soils (2 mg kg\(^{-1}\)) [21] and ranged from 0.56 mg kg\(^{-1}\) in acidic soils (such as Tepsus acid sulphate soils) to 1.19 mg kg\(^{-1}\) in neutral soils (such as the Telecom soil series). Thus, the rice crops were in the insufficient Zn nutritional condition. These soils contained less available Zn than is commonly accepted as corresponding to the critical level for plant growth.[22] The results indicated that the total Zn – as an indicator of the potential capacity of soils to supply Zn for crop production [2] – was the most important factor, influencing the adsorption–desorption processes of the available Zn. These confirmed results reported by Pickering [23] and Obrador et al. [24].

In contrast to the available Zn (double acid), the WE Zn fraction was less than 0.52 mg kg\(^{-1}\) in all soils which confirmed the pervious finding of this study that the available Zn contents of the selected soils were under the critical level for rice crops (0.6 mg kg\(^{-1}\) by NH\(_4\)OAc).[21] Despite the Zn deficiency disorder in paddy soils of the study areas, the WE and Org fractions were the most phyto-available forms of Zn for plant uptake.[9,20,25] The latter fractions were more than 1 mg kg\(^{-1}\), whereas the AF of almost all soils was medium, with the exception of Telemong series, which had the highest AF. The results of the AF showed that the WE plus Org fractions were the main fractions that influenced the predictability of the most potentially available amounts of Zn. It can be concluded that when the WE pools depleted, the Org fraction came to account for replenishing the available Zn pool in the soil.[24] In spite of the differences found between the total Zn concentration and the physicochemical properties of the extracted soils, the order of Zn fractions in all soils (based on Duncan’s separation of average analysis) was in the following order: WE < Cry < MN < Org < Amor < Res. Different literatures reported the same trend...
in their studies.[12,13] In these soils, therefore, native Zn appeared to be predominantly associated with the crystalline lattices of the minerals. Processes of Zn mobilization–immobilization were affected not only by a special extractant, but also a variety of soil properties.[23,24]

Compared to sequential Zn fractions of the soil samples at 30 days, the analysis of 60-day samples showed a different order under the longer period of submerging. Therefore, the proportion of the extracted Zn fractions was in the new order as follows: WE < MN < Cry < Org < Amor < Res. This order happened as the WE, Org and Cry fractions decreased by 7, 8.5 and 7.3%, while the Amor, Mn and Res fractions increased by 2.9, 6 and 3%, respectively. It should be considered that the submerged duration had a significant effect on the concentration of WE (p < 0.001), Org (p < 0.05) and Cry (p < 0.01). The results of this study confirmed the findings of Wijebandara [8] and Talukder et al. [26]. Furthermore, the results emphasized the importance of the flooding length on the transformation of applied Zn, especially on WE and Org fractions.[8]

The correlation between the soil characters and the residual and non-residual fractions was strongly dependent on their soil geochemical backgrounds on the basis of previous studies, Obrador et al. [24] and Wijebandara [8]. The residual fraction showed correlation with the soil matrix (clay content), whereas the phyto-available parts of non-residual fractions (WE and Org) associated with soil geochemical characteristics (CEC and OC). Also, among the less stable and non-residual fractions, MN, and to a lesser extent Cry and Amor fractions had the highest correlation with clay content due to increase in the degree of crystallization of Amor, MN and Cry constituents, respectively. These confirmed results reported by Obrador et al. [24]. The soil properties are the major controlling factors that affect the phyto-availability [27] and (im)mobilization processes of metals [24]. The influence of tropical soil characters on cation adsorption–desorption processes in Brazilian Ultisols and Oxisols, where Zn fractions showed significant positive correlation with CEC, but no relationship

Table 7. Multiple linear regression models between zinc fractions and soil characters.

| Fractions | Model components (stepwise) | B     | R      | Sig   |
|-----------|-----------------------------|-------|--------|-------|
| WE        | (Constant)                  | 0.17  | 0.52   | 0.00**|
|           | CEC                         | 0.03  |        |       |
|           | Soil MN                     | −0.004|        |       |
|           | OC%                         | 0.07  |        |       |
| Org       | (Constant)                  | −0.1  | 0.59   | 0.00**|
|           | Mg                          | −0.01 |        |       |
|           | OC                          | 0.19  |        |       |
| Amor      | (Constant)                  | 4.17  | 0.15   | 0.01* |
|           | EC                          | −0.01 |        |       |
| Mn        | (Constant)                  | 0.72  | 0.54   | 0.00**|
|           | Clay                        | 0.03  |        |       |
|           | OC                          | −0.49 |        |       |
|           | Mg                          | 26.84 |        |       |
|           | Ca                          | −0.24 |        |       |
| Cry       | (Constant)                  | 0.23  | 0.52   | 0.00**|
|           | OC                          | 0      |        |       |
| Res       | (Constant)                  | 32.46 | 0.94   | 0.00**|
|           | Clay                        | 1.22  |        |       |
|           | OC                          | −12.96|        |       |
|           | CEC                         | −2.23 |        |       |
|           | FE                          | −0.07 |        |       |
| SUMF      | (Constant)                  | 40.11 | 0.9    | 0.00**|
|           | Clay                        | 1.76  |        |       |
|           | OC                          | −19.83|        |       |
|           | CEC                         | −2.36 |        |       |
|           | SoilMn                      | −0.275|        |       |
| Total     | (Constant)                  | 46.42 | 0.84   | 0.00**|
|           | EC                          | −0.26 |        |       |
|           | SoilMn                      | 0.44  |        |       |
|           | Fe                          | −0.02 |        |       |
|           | CEC                         | 1.48  |        |       |
| Total     | (Constant)                  | 11.05 | 0.81   | 0.00**|
|           | Res                         | 0.9   |        |       |
|           | Amor                        | 1.24  |        |       |
with the pH of the soil[28]. Also, in 57 Indian soils (eight orders, including Oxisols and Ultisols), the total Zn concentration in soils showed highly significant correlation with clay content, but no correlation with the pH and the other soil properties.[29]

The multiple linear correlation analysis among sequential extracted fractions of Zn and soil characters confirmed the finding of correlation analysis. In all studied soils, various Zn fractions significantly and positively correlated with each other because of the dynamic equilibrium among the different pools of Zn in soils. This showed that immediately after WE and Org depletion in the soil, the available pools of Zn replenished with the other fractions. In this case, a high positive correlation between the WE and Org and also between Amor and Cry stressed the influence of these fractions on the
availability of Zn in soils. The high correlation between the Res and SUMF and the total Zn in soils determined the dependence of Res on them. These findings were in line with results reported by Prasad et al. [30]. The dynamic equilibrium among different pools of soil Zn also indicated that the Zn fractions depleted as follows: WE, Org, Cry and MN. Similar results were reported by Mandal and Mandal [31]. In all soil types, concentration of all extracted forms of Zn increased with increase in the amount of total Zn. By comparing the three soil reaction (pH) classes, it was evident that not only soluble fractions (WE and Org), but also low or insoluble forms showed the same trend. These results confirmed that the total Zn content was the main factor affecting the concentration of Zn fractions. The findings of current research confirmed the results reported by Catlett et al. [32], Kabata-Pendias [27] and Voegelin et al. [33]. Considering the effects of the selected soil characters on soil Zn fractions, the results of multiple linear regressions indicated that the WE significantly correlated with OC and CEC (R = 0.52), whereas the Org only significantly correlated with OC (R = 0.59). These results suggested that the OC and CEC increased the potential availability of phyto-available fractions of Zn in the soil. On the other hand, among various variables interred in the model (10 soil properties), 52–59% of the behaviour of WE and Org fractions can be described by only two soil factors – OC and CEC. The results were in line with Obrador et al. [24] findings in Brazilian tropical soils.

Conclusion

On the basis of the results, it can be concluded that the distribution of native soil Zn in paddy fields depended on the soil characters, especially CEC, clay content and OC. Zinc fractions in the selected soils (30 days, submerged) mainly distributed in the residual fractions followed by the Amor, Org, MN, Cry and WE fractions, whereas at 60 days submerged soil samples, the order was as follows: WE < MN < Cry < Org < Amor < Res. Zinc in acidic soils mostly occurred in the Res (70–74%) and the Amor (8–10%) fractions, while Zn in the neutral and nearly neutral soils existed in the Res (50%) and followed by the Amor (6%). In spite of the significant differences that existed among the residual fractions in the extracted soils, it was clear that the Res fraction was the largest portion of Zn fractions in all the soil series. Also, water-soluble plus exchangeable forms showed the similar pattern, but they were the smallest portion. The available Zn was influenced by the phyto-available fractions – WE and Org. The CEC, clay content and OC were the most important factors in controlling the distribution of native Zn in soils. Furthermore, the results of multiple linear regression (stepwise) analysis confirmed the effect of three latter soil properties on Zn fractions. Also, the extractability and solid-phase fractionation of Zn in two different submerged conditions showed the importance of the time of Zn application. Furthermore, the critical level was only useful over a limited range of soils and crops as they were closely related to the conditions under which they were determined. Also, the potential mobility of Zn in the soil–plant continuum might be assessed based on their absolute and relative content of metal fractions that weakly bound to the soil components. Finally, the results of this study suggested that the time of Zn application, flooding/pre-flooding and the effect of soil controlling factors on Zn fractionation and bioavailability are the areas that deserve more studies and closer attention.

Disclosure statement

No potential conflict of interest was reported by the authors.

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