**Theory**

The two component first order model can be schematically represented for the DMT-HFAO system as:

kRkT

 SP→Psol→PHFAO (1)

where PHFAO is P adsorbed by HFAO, Psol is solution P, SP is P in solid phase, kR is the rate constant representing P release (De Jager and Classens 2005) and kT is the rate constant describing the P transport through the membrane (0.09+ 0.01h-1; Freese*et al*. 1995). The desorption kinetics is representedby two-component first order model by assuming two pools: pool A (SPA), the pool with fast release kinetics, and pool B (SPB), the pool with the slow release kinetics, The mass balance equation for the total exchangeable solid-phase soil P (SPtotal) at time t=0 is therefore:-

 SPtotal= SPA0+SPB0 (2)

Where SPA0 is initial amount of P in pool A and SPB0 is initial amount of P in pool B. The mass balance equation at time t will therefore be

SPt= SPA(t)+SPB(t) (3)

Considering the decline in SPA and SPB follow first order kinetics, the integrated rate laws for the decrease of SPA and SPB will be

SPA(t)= SPA0e-kAt and SPB(t)= SPB0e-kBt (4)

Where kA and kB are conditional first-order order rate constants (day-1) for P desorption from respective pools (Pools A and B).. The total solid phase soil P (SPtotal (t)) remaining at time t will be given by

 SP total(t)= SPA0e-kAt + SPB0e-kBt (5)

The total amount of P released at time t is expressed as

PR(t)= SPA0-SPA(t)+SPB0-SPB(t)

 = SPA0 - SPA0e-kAt + SPB0 - SPB0e-kBt (6)

 =SPA0(1- e-kAt) + SPB0(1-e-kBt)

It was assumed that the rate constant of P release from the soil is equal to the rate constant of P adsorption, which can be obtained by plotting natural logarithm of P adsorbed by DMT-HFO against time. The rate constants, kA and kB,can be determined from the slopes by splitting the respective P pools into pool A and B, considering the pattern of P release over time. Although long-term P desorption can be described in terms of two discrete P pools (viz. ‘fast’ and ‘slowly’ desorbable P (Lookman et al., 1995), one should bear in mind that most soils appear to exhibit a continuum of desorbable P forms. Thus, it is reasonable to postulate the sum of kA and kB, as a relevant index worth considering in relation to plant yield parameters.

### Description of the Soil Sampling Areas

The soil samples were collected from six sites: Bako, Guto-gida, Bishoftu, and Mechara areas of Oromia National Regional Stateand Gununo and Hegere-selam areas in [Southern Nations, Nationalities and Peoples' Region](http://en.wikipedia.org/wiki/Southern_Nations%2C_Nationalities_and_Peoples%27_Region) (SNNPR), Ethiopia (Figure 1).Bako is found in East Wollega Zone, 260 km from Addis Ababa, western Ethiopia. It lies at 9o6' N and 37o09' E, at 1650 meters above sea level. The area has a unimodal rainfall pattern totaling annually 1244 mm (Wakene and Heluf, 2003). The average air temperature is 20.6 °C. The soil type of the study area is Alfisols (Udalf), reddish brown with pH from strongly acidic to slightly acidic. Guto-gida district is also located in East Wollega, Oromia Regional State, Ethiopia, at a distance of 320 km from Addis Ababa lying between 08o 59' and 09o 06' N latitude and 37o 51'and 37o 09' E longitude at an altitude of 1650 meters above sea level. The average annual rainfall is about 1780 mm which is characterized by a unimodal rainfall pattern with an annual mean temperature of 20.7°C. According to FAO (1990) classification, the soil class of the study area is Nitisol. The pH of these soils varies from strongly to moderately acidic.

Bishoftu town is located on the escarpment of the Great Rift Valley, 47 km south of Addis Ababa, in Oromia National Regional State. Topographically, the town is located in tepid to cool sub-moist mid highland at an altitude of about 1920 meters above sea level with moderate weather condition. The absolute location of Bishoftu is 8o 44' 40'' N and 38o 59' 9'' E. The position of the town on the escarpment of the Great Rift Valley influences the climate of the area. The average temperature is 20°C with an annual mean rainfall is 850 mm. The soil types are HaplicAndosol, Vitric Andosol and EutricVertisol.The black clay soils are medium to slightly acidic with the majority of them being slightly acidic whereas gray soils are neutral (Murphy, 1968).Mechara is the district capital of Darolebu in Oromia Region, Western Hararghe zone, situated at a distance 430 km from Addis Ababa located at 08°36” N latitude and 40°19” E longitude, andat an altitude of 1773 meters above sea level. It is characterized by an average annual temperature of 25.6°C and annual rainfall of 1294 mm while precipitation is bimodal and shows a strong seasonal variation. The soils of the study area are VerticLuvisoils, EutricCambisols (Asrat*et al*, 2008), while the dominant one is Nitisol.

Hagereselam is a capital district of Hula located in the [Sidama Zone](http://en.wikipedia.org/wiki/Sidama_Zone) of the [Southern Nations, Nationalities and Peoples' Region](http://en.wikipedia.org/wiki/Southern_Nations%2C_Nationalities_and_Peoples%27_Region). It has a latitude and longitude of 6o29' N38o 31' E﻿ / ﻿﻿ / 6.483; 38.517 and an elevation of about 2759 meters above sea level. The average annual rainfall is 1300 mm and the average annual temperature is 14 °C. Gununo is one of the districts in Wolayita zone, [Southern Nations, Nationalities and Peoples' Region](http://en.wikipedia.org/wiki/Southern_Nations%2C_Nationalities_and_Peoples%27_Region), having an altitude 2300 meters above sea level with low land and high land agroecology. It is located at 7º 58'' N and 37º 35'' E. Its annual average temperature is 21.86 °C and the mean annual rainfall is 1200 mm. The types of soils in the area according to FAO classification are dominantly EutricNitisols or according to USDA classificationAlfisols (Tesfaye,2003; Laekemariam et al., 2016).

and tissue P content of the maize plant are shown in Table 3.

### Selected physical and chemical properties of the soils

Determination of physical and chemical properties of soils was carried out before desorption procedure and tabulated in Table 1. The pH(H2O) was determined by dispersing 20 g dried soil in 50 mL deionized water and stirring for 10 minutes and measuring the pH of the soil suspension after 30 minutes (Okalebo*et al*., 2002). The pH(KCl) of the soil samples was determined in the soil suspension by dispersing 20 g of dried soil in 50 mL of 1*M* KCl (1:2.5) and shaking end-over-end at 20 rpm for 2 h (Freese *et al.,*1995). Available phosphorus was determined using Bray and Kurtz (Bray- 1P) method (0.03 *M* NH4F + 0.025 *M* HCl) (Bray and Kurtz, 1945). Total soil P (PT) was determined on sub-samples of 0.3 g soil with the addition of 5 mL concentrated H2SO4 and heating to 360 0C on a digestion block with subsequent stepwise (0.5 ml) additions of H2O2 until the solution was clear (Thomas *et al.,*1967). Exchangeable aluminum was determined by adding 10 mL of NaF to 12 g soil sample leached with 30 mL of 1N KCl (1:2.5) and titrating the released alkali with 0.02M standard solution of HCl. Dithionite citrate bicarbonate (DCB)-extractable crystalline Fe and Al (FeDCB and AlDCB) and acid oxalate in darkness (AOD) extractable FeAOD and AlAOD were determined as described by Shang and Zelazny (2008). Organic C was determined by dichromate oxidation method using GENESUS-20 spectrophotometer as described in Motsara and Roy (2008). Particle size distribution of the soils was determined using hydrometer method after dispersion of the soil with sodium hexametaphosphate, Na6(PO3)6 (Sahlemedhin and Taye, 2000).

* 1. **Synthesis of crystalline and amorphous Fe-Al binary mixed oxides powders**

Using gel evaporationmethod (Gulshan*et al*., 2009), powder sample of Fe-Al (10% mol) mixed oxide was synthesized fromFe(NO3)3·9H2O (Sigma-Aldrich, Germany) and Al(NO3)3·9H2O (Uni-chemchemicalreagents, AR) dissolved in ethyleneglycol(Baker Analyticalreagent, USA) at molar ratio of 1:3 of total metal ion to ethylene glycol with addition of deionized wáter just enough to dissolve the starting materials. The solution was then refluxed in a 250 mL flask at 65°C for 24 h to get hydrosol. The hydrosol was dried at 100 °C for 24 h to obtain xerogel. Finally, thexerogel was grounded and calcined at 300 °C for 2 h (crystallinephase). The calcined crystal sample is referred as calcined powder sample (CPS). Another sample (for amorphous phase) was also prepared by the same procedure without calcinations and referred as amorphouspowdersample (APS).

* 1. **Characterization**

The phase of the as-synthesized powder was identified by XRD equipped withCuKα radiation (λ= 1.5405 Å) operated at 40 kVtubevoltage and 40 mAtubecurrentwith a scanningrate of 4 min-1 at a stepscan of 0.02. The crystallite size was determined from the XRD peaks using Scherer formula (Persson*et al*., 1996). The surface functional groups of the as-synthesized samples were determinedusingFourier transforminfrared(FTIR) spectrometer (Spectrum 65, PerkinElmer) in therange 4000-400 cm-1usingKBrpelletizer. The morphology of the solids was determined by scanning electron microscopy (SEM) using a Hitachi TM1000 with backscattered electrons detector and EDX detector.Adsorption properties were measured under N2 atmosphere at −196 oC in a Micromeritics instrument ASAP 2420 device. The isotherms were registered, approximately to 200 mg of each sample were outgassed at 150 ºC for 16 h under high vacuum. Thus, the surface areas of the materials were estimated using the Brunauer-Emmet-Teller (BET) method and theirmicropore and externalsurfaceareasweredeterminedbythe t-plotmethod. Poresizedistributionswerepredictedbyapplyingthe BJH method. The total porevolumewastakenfromtherelativepressureclosetounity (P/Po =0.98). Thermogravimetricanalysis (TGA) wasperformedusing a PerkinElmer TGA7 instrument in thetemperaturerange of 30 ºCto 900ºC under air flow at a heatingrate of 20omin-1

Table S1: Selected physical and chemical properties of the soils before incubation

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
|  |   | Sampling site |   |   |   |
|  | Bako | Bishoftu | Gununo | Gutogida | Hegereselam | Mechara |
| Parameters |  |  |  |  |  |  |
| pH (KCl) | 3.7 | 6.8 | 3.5 | 3.8 | 4.5 | 4.8 |
| pH(H2O) | 4.6 | 7.3 | 4.3 | 4.5 | 4.9 | 5.3 |
| \* Extractable Ca (cmol/kg) | 2.6 | 13.4 | 1.2 | 1.3 | 5.4 | 5.9 |
| \*Extractable Mg(cmol/kg) | 2.0 | 6.8 | 0.5 | 0.7 | 3.3 | 4.5 |
| \*Extractable K (cmol/kg) | 0.4 | 0.8 | 0.2 | 0.3 | 0.5 | 0.7 |
| \*Exchangeable Al (cmol/kg) | 2.00 | 0.01 | 7.00 | 4.00 | 0.10 | 0.03 |
| AOD extractable Fe (%) | 0.14 | 0.13 | 0.13 | 0.15 | 0.56 | 0.94 |
| AOD extractable Al (%) | 0.050 | 0.110 | 0.130 | 0.001 | 0.150 | 0.700 |
| DCB extractable Fe (%) | 0.52 | 0.60 | 0.52 | 0.54 | 1.20 | 1.90 |
| DCB extractable Al (%) | 0.026 | 0.010 | 0.020 | 0.020 | 0.010 | 0.080 |
| DCB extractable Mn (%) | 0.056 | 0.060 | 0.210 | 0.090 | 0.300 | 0.120 |
| OC (%) | 2 | 1.4 | 1.9 | 2.3 | 2.6 | 1.8 |
| Total N (%) | 0.32 | 0.16 | 0.19 | 0.27 | 0.34 | 0.34 |
| Available P (mg/kg) | 3.4 | 17 | 3 | 3.6 | 5.20 | 5.8 |
| % clay | 36 | 15 | 28 | 30 | 17 | 46 |
| % silt | 8 | 16 | 16 | 17 | 19 | 12 |
| % sand | 56 | 69 | 56 | 53 | 64 | 42 |
| Textural class | sandy clay | sandy loam | sandy clay loam | sandy clay loam | sandy loam | clay |

\*NH4Ac, Ammonium Acetate extractable

Table S2. BET specific surface area (m2/g) of CPS, APS and APS-Fe

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sample | SBET | Smicro | Sext | Vpor(BJH) | Pore volume (cc/g) |
| CPSAPSAPS-Fe | 48.724211.351617.1159 | 0.68840.47610.3442 | 48.035710.875516.7717 | 0.0135800.0029050.004550 | 0.0024040.0051820.007907 |

**100 µm**

**CPS**

**50 µm**

**APS**

Figure S1. SEM micrographs of amorphous (APS) and crystalline (CPS) Fe-Al binary composite

Table S3: Phosphate extracted by subsequent P-fractions of DMT-HFAO and DMT-HFO

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  |  |  |  |  |  | P-fractions |  |  |  |
| Site | Treatment | Sorbent | NaHCO3-Pi | NaOH-Pi | d/HCl-Pi | C/HCl-Pi | NaHCO3-Po | NaOH-Po | C/HCl-Po | H2SO4-P |
| Bako | BaT0 | DMT-HFO | 17.44x | 54.8g | 10.85c | 15.68e | 20r | 10.58w | 28.93e | 197.43a |
|  |  | DMT-HFAO | 13.3y | 22.9h | 7.9d | 10.87f | 36.67s | 10.81w | 29.6e | 198.32a |
|  | BaT1 | DMT-HFO | 25.89a | 61.76i | 13.73e | 17.11g | 37.38t | 21.82x | 32.32r | 235.64b |
|  |  | DMT-HFAO | 21.5b | 43.26j | 11.01f | 15.1h | 44.69u | 20.18y | 29.9s | 219.56c |
|  | BaT2 | DMT-HFO | 38.01c | 62.45k | 15.05x | 17.97i | 58.9a | 27.93a | 44.12p | 237.54d |
|  |  | DMT-HFAO | 30.4d | 50.8l | 11.7y | 18.1i | 54.88b | 26.35b | 46.6q | 198.88e |
|  | BaT3 | DMT-HFO | 20.15e | 57.72m | 12.34h | 16.73j | 27.07x | 20.33c | 30.93a | 316.51f |
|  |  | DMT-HFAO | 17.9f | 28.3n | 8.9i | 12.13k | 42.29y | 14.96d | 23.1b | 308.78g |
| Bishoftu | BiT0 | DMT-HFO | 32.8a | 18.11e | 42.42y | 19.45x | 31.39r | 30.47c | 25.57i | 257.13p |
|  |  | DMT-HFAO | 31.1b | 16.73f | 37.08z | 18.36x | 30.5s | 29.62d | 24.51j | 218.21q |
|  | BiT1 | DMT-HFO | 43.37c | 23.5g | 53.44e | 21.94y | 60.95a | 35.48x | 26.61k | 261.75r |
|  |  | DMT-HFAO | 38.5d | 18.14h | 47.56f | 21.1y | 59.55b | 13.42y | 22.17l | 236.68s |
|  | BiT2 | DMT-HFO | 48.53x | 27.66i | 60.94c | 23.82a | 60.41x | 22.58e | 23.08u | 344.75g |
|  |  | DMT-HFAO | 42.7y | 21.37j | 55.1d | 22.79a | 43.37y | 20.54f | 23.79v | 322.2h |
|  | BiT3 | DMT-HFO | 66.3w | 32.72k | 75.14r | 27.42b | 47.61c | 46.45g | 28.16x | 241.45i |
|  |  | DMT-HFAO | 53.17u | 27.17l | 69.09s | 26.5b | 58.37d | 51.29h | 25.65y | 214.71j |
| Gununo | GnT0 | DMT-HFO | 9.67e | 12.8a | 6.6p | 14.63u | 25.15c | 11.72i | 40.82q | 99.84c |
|  |  | DMT-HFAO | 15.04f | 12.26a | 6.29p | 17.48v | 24.1c | 36.61j | 15.88r | 75.03f |
|  | GnT1 | DMT-HFO | 14.6g | 16.69b | 12.17q | 19.98w | 30.94d | 17.51k | 52.08s | 128.46e |
|  |  | DMT-HFAO | 19.85h | 15.9c | 10.14r | 28.83x | 31.74d | 21.98l | 21.24t | 112.45d |
|  | GnT2 | DMT-HFO | 11.5i | 13.91d | 9.38s | 16.08y | 25.15e | 13.87m | 55.08v | 197.06g |
|  |  | DMT-HFAO | 17.64j | 13.8d | 9.2s | 21.51z | 32.8f | 29.72n | 23.24u | 164.39h |
|  | GnT3 | DMT-HFO | 12.83l | 14.79n | 8.95t | 16.52a | 25.88g | 14.65o | 59.32a | 234.87i |
|  |  | DMT-HFAO | 18.48m | 14.76n | 9.24v | 23.3b | 37.36h | 27.62p | 18.54b | 212.66j |

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Site | Treatment | Sorbent | NaHCO3-Pi | NaOH-Pi | d/HCl-Pi | d/HCl-Pi | NaHCO3-Po | NaOH-Po | C/HCl-Po | H2SO4-P |
| Guto-gida | GGT0 | DMT-HFO | 34.37a | 38.72i | 17.48q | 30.02y | 27.64h | 29.15x | 17.15e | 177.07n |
|  |  | DMT-HFAO | 27.64b | 18.47j | 6.68r | 26.73z | 25.05i | 28.41x | 13.02f | 161.57o |
|  | GGT1 | DMT-HFO | 41.19c | 44.86k | 18.1s | 34.23a | 37.46j | 42.47y | 20.58g | 207.45p |
|  |  | DMT-HFAO | 31.73d | 24.83l | 11.32t | 32.23b | 32.65k | 36.69z | 15.86h | 206.99p |
|  | GGT2 | DMT-HFO | 25.91e | 34.93m | 16.56v | 23.74d | 13.91l | 18.38a | 11.82j | 317.03a |
|  |  | DMT-HFAO | 22.39f | 14.3n | 7.06u | 20.49e | 13.85m | 22.1b | 7.97k | 249.35b |
|  | GGT3 | DMT-HFO | 31.71g | 36.74o | 16.95w | 27.85f | 22.74n | 24.66c | 14.21l | 345.48c |
|  |  | DMT-HFAO | 26.26h | 21.56p | 9.12x | 24.84g | 19.3o | 25.48d | 10.51m | 301.64d |
|  |  |  |  |  |  |  |  |  |  |  |
| H.selam | HST0 | DMT-HFO | 8.23a | 21.57x | 7.45r | 63.37l | 12.25u | 40.77d | 53.87m | 809.62p |
|  |  | DMT-HFAO | 13.45b | 21.72x | 5.62s | 41.76m | 20.28v | 10.03e | 51.76l | 774.16q |
|  | HS1 | DMT-HFO | 14.56c | 31.28a | 10.09p | 82.57n | 23.05x | 49.97f | 75.63o | 809.64r |
|  |  | DMT-HFAO | 26.01d | 36.29b | 8.56q | 67.2o | 25.81y | 31.99g | 69.5n | 768.95s |
|  | HST2 | DMT-HFO | 15.87x | 33.87c | 11.05u | 87.23p | 25.07a | 54.88h | 79.68o | 815.49x |
|  |  | DMT-HFAO | 28.7y | 29.65d | 10.06v | 74.9q | 29.92b | 46.93i | 80.66p | 792.8y |
|  | HST3 | DMT-HFO | 20.1z | 38.1e | 13.63w | 99.38r | 33.75c | 59.26j | 94.72s | 894.53t |
|  |  | DMT-HFAO | 34.44w | 35.91f | 12.11x | 97.03s | 32.78c | 56.78k | 90.26t | 797.12v |
|  |  |  |  |  |  |  |  |  |  |  |
| Mechara | MeT0 | DMT-HFO | 23.29a | 5.9i | 8.35o | 30.33v | 30.41d | 25.11l | 34.3z | 280.09j |
|  |  | DMT-HFAO | 5.39b | 15.8j | 6.83p | 38.76bw | 22.81e | 28.69m | 15.68a | 214.28i |
|  | MeT1 | DMT-HFO | 28.82c | 29.82k | 15.83q | 56.57x | 41.57f | 47.9n | 59.43b | 269.22l |
|  |  | DMT-HFAO | 25.57d | 22.47l | 11.7r | 45.31y | 28.04g | 55.26o | 23.62c | 208.08k |
|  | MeT2 | DMT-HFO | 24.27e | 19.07m | 13.58s | 44.65a | 34.35h | 40.17v | 50.48e | 313.9n |
|  |  | DMT-HFAO | 17.96f | 19.87m | 9.67t | 43.24a | 25.03i | 42.62w | 27.53f | 261.57m |
|  | MeT3 | DMT-HFO | 25.76g | 20.97n | 14.73v | 47.58b | 32.17j | 42.38x | 76.63g | 340.5o |
|  |  | DMT-HFAO | 19.12h | 20.33n | 10.12u | 43.21c | 29.68k | 51.29y | 33.74h | 281.67p |

Table S4. DMT-HFAO rate constants, half-life and predicted days for depletion of slow labile pool of six sites soil.

|  |  |  |  |
| --- | --- | --- | --- |
| Site | Rate constants (day-1) | Half-life (days) | Predicted days for depletion of phosphate |
| kA | kB | Pool A | Pool B | pool B |
| Bako | 0.099±0.008 | 0.022±0.000 | 7.0 | 31.0 | 314 |
| Bishoftu | 0.104±0.007 | 0.018±0.001 | 6.7 | 38.5 | 384 |
| Gununo | 0.127±0.014 | 0.023±0.001 | 5.4 | 30.1 | 300 |
| Guto-gida | 0.099±0.009 | 0.023±0.002 | 7.0 | 30.1 | 300 |
| Hagere-selam | 0.111±0.013 | 0.015±0.001 | 6.2 | 46.2 | 461 |
| Mechara | 0.131±0.012 | 0.015±0.002 | 5.3 | 46.2 | 461 |

± Standard error