



## A Review on Possible Influence of Clays and Soil Clay Minerals on Soil Fertility

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### Abstract

Clays and clay minerals are of great importance in soil fertility. The clay fraction of soil and in particular the kind and amount of the respective clay minerals present determines the chemical and physical properties of the soil. It influences the ease or difficulty of release of plant nutrient ions and therefore plays an important role in plant nutrition and soil fertility. In managing soils for agricultural production, soil and the amount of clay present are very important. This review discusses the role of clays and clay mineralogical properties in soils as a measure of developing stable agricultural environment for maximum quality level of soil fertility and productivity.

**Keywords:** *Clays, clay minerals, soil physico-chemical properties, soil fertility, soil productivity, cation exchange capacity*

### 1. Introduction

Soils vary in their fertility level due to differences in soil properties (Foth and Ellis, 1997). Soil fertility is defined as a condition of the soil that enables it to provide nutrients in adequate amounts and in proper balance for the growth of specified plants when other growth factors, such as light, water, temperature, and physical condition of soil, are favorable (van der Watt and van Rooyen, 1995). It is the component of overall soil productivity that deals with its available nutrient status, and its ability to provide nutrients out of its own reserves and through external applications for crop production. It combines several soil properties (biological, mineralogical, chemical and physical), all of which affect directly or indirectly nutrient dynamics and availability (Eghball, 2002). Soil fertility is a manageable soil property and its management is of utmost importance for optimizing crop nutrition on both a short-term and a long-term basis to achieve sustainable crop production (Havlin et al., 2005).

The reaction of soils that greatly influences soil fertility is determined by its clay fraction, especially the mineralogical composition (Douglas, 1989). Studies by Parfitt et al. (1997) have revealed that soil clay mineralogy influences organic matter dynamics in soils, sorption and ion reactions and fixation of nutrients. These effects of the clay minerals are enhanced or compromised by interaction with other soil properties such as pH and electric conductivity. Physico-chemical and clay mineralogical properties of soil therefore clearly interact to influence soil fertility. This interaction varies with soils because of the differences that exist in soil orders.

This review therefore collates and synthesizes available information on clays and clay minerals and their influence on soil fertility for agricultural purposes. Clays and clay minerals are discussed in relation to the environment, soil properties and soil management practices with the intent of better understanding the link between soil clay mineralogy and agriculture.

### 2. Soil clay

Clay is a naturally occurring material composed primarily of fine-grained minerals ( $< 2 \mu m$ ), which show plasticity through a variable range of water content, and which can be hardened when dried and/or fired (Beckett, 1995). Clays are distinguished from other fine-grained soils by differences in size and/or mineralogy (Guggenheim et al., 1995). The clay content in the soil could have a great influence on water and nutrient retention (Brady and Weil, 1999). Water retention is quite high in soil with higher clay content and can result in problems such as water-logging which results in matric-potential where water is retained but not available to plants and this may cause root infections for plants (Brady and Weil, 1999). Plant roots may also find it difficult to penetrate through clayey soil because of the rigid structure.

Clay is composed of particles that have a negative charge on them and have a large surface area (Beckett, 1995). This enables the soil to attract and hold on to mineral nutrients that are positively charged such as magnesium, potassium and calcium, which are vital to the growth of healthy plants. Good nutrient retention is one of the positive qualities of clay soil. Good soil for plant growth must retain the required amount of water, provide good aeration and promote nutrient absorption, but it can be difficult to work with if the clay content is in excess, because of the hardness and compact soil structure (Hagan et al., 2010). However, with the addition of organic material such as compost and manure, soil structure and tilth can be greatly improved.



Clay soil is also subject to formation of cracks when it is dry, especially if the clay mineralogy is dominated by 2:1 swelling clays (Hagan et al., 2010). This can harm the plant roots as it may cause root breakage or impedes transportation of nutrients from the soil up to the plants, it can also prevent seedling emergence (Gregory et al., 2006). Soils with a higher percentage of clay and silt, which naturally have more pore space, have a lower bulk density than sandier soils (Hagan et al., 2010). Clay therefore influences soil chemical reactions depending on its mineralogical composition.

### **3. Soil clay minerals**

The clay fraction of soil is dominated by clay minerals which control important soil chemical properties including sorption characteristics and ion exchange reactions in soils (Dixon and Schulze, 2002; Brigatti et al., 1996; Barrow, 1999). Clay minerals are hydrous aluminium phyllosilicates, sometimes with variable amounts of iron, magnesium, alkali metals, alkaline earth metals and other cations, (Joussein et al., 2005). Clays and clay minerals occur under a fairly limited range of geologic conditions (Velde et al., 2003). They are derived from weathering of rocks and are very common in fine grained rocks such as shale, mudstone, siltstone, slate and phyllite (Van der Merwe et al., 2002).

#### **3.1. Clay minerals formation in soils**

Clay minerals form in many different environments, including the weathering environment, the sedimentary environment, soil horizons, volcanic deposits and the diagenetic-hydrothermal environment (Brady and Weil, 1999; Foley, 1999). Most clay minerals form where rocks are in contact with water, air, or steam. Intense weathering produced in a hot and moist climate can lead to major changes in mineral structure and the conversion to hydrous oxides (Foley, 1999). Some of the elements that are released during weathering of these rocks reform and crystallise in a different structure forming secondary minerals that include vermiculite, montmorillonite and kaolinite (Hillier, 1995).

#### **3.2. Structure of clay minerals**

Clay minerals are developed by the formation of sheets, derived from linking of octahedral and tetrahedral units to form “flat” layers (Brady and Weil, 1999). Details of the basic structure of clay minerals have been discussed in several texts (Olis et al., 1990; Brady and Weil, 1999). On the basis of the number and arrangement of tetrahedral and octahedral sheets contained in the crystal units or layers, silicate clays are classified into two different groups (Brady and Weil, 1999) i.e. 1:1 type minerals and 2:1 type minerals.

The 1:1 type minerals are made of one tetrahedral sheet and one octahedral sheet bonded together to form a layer (Brady and Weil, 1999). Kaolinite is the most common member of this group, which is characterized by no expansion, little isomorphous substitution, less plasticity, stickiness, cohesion, shrinkage or swelling (Van der Merwe et al. 2002; Brady and Weil, 1999). Kaolinite-containing soils are easy to cultivate for agriculture and with some nutrient supplementation from manure and fertilizer, can be very productive (Brady and Weil, 1999). The crystal units of 2:1 type minerals are characterized by an octahedral sheet sandwiched between two tetrahedral sheets (Brady and Weil, 1999). This group is comprised of smectite, vermiculite, the micas (illite) and chlorite (Brady and Weil, 1999). Minerals in this group have high cation exchange capacity (CEC) due to their large surface area, a shrink and swell potential (Mathe et al., 2007), and interlayer expansion. Some of 2:1 clay minerals such as montmorillonite and vermiculite manifest isomorphous substitution of Mg for some Al in the octahedral sheet (Brady and Weil, 1999; Van der Merwe et al. 2002). With  $Mg^{2+}$  substituting for  $Al^{3+}$  there are fewer positive charges to neutralize the negative charges and a large permanent (negative) charge results. In contrast, there are also variable or pH-dependent charges that are formed by protonation and deprotonation of functional groups like –OH group. Composition of kaolinite is close to ideal, since there is very little or no isomorphous substitution, resulting in no permanent charges (Brady and Weil, 1999; Van der Merwe et al. 2002). In addition, kaolinite has a small amount of variable charge related to dissociable OH groups attached to Al at the edges of the crystal, where the structural regularity ends.

In comparison, soil fertility is generally high in high-activity clays such as smectites and other 2:1 clay minerals than it is in 1:1 clay minerals such as kaolinite, which tend to decrease aggregate stability, because of its small surface area and low CEC (Leinweber and Schulten, 2000 and Six et al., 2000). Kaolinite clays also have only the edges contributing to CEC, while 2:1 clays have the edges and isomorphous substitution.

### **4. Effects of soil mineralogy on soil fertility**

Soil mineralogy affects soil fertility through its effects on soil properties which play a significant role in the fertility status of the soil. These include organic matter accumulation, nutrient availability, fixation of nutrients, soil structure, water holding capacity, root penetration and growth.



#### **4.1. Organic matter accumulation**

Soil organic matter (SOM) plays an important role in enhancing fertility, productivity and sustainability of soils and agricultural production (Ransom et al., 1998). Organic matter, like clay, has a high surface area and is negatively charged with a high CEC, making it an excellent supplier of nutrients to plants (Myers, 1995). In addition, as OM decomposes, it releases nutrients such as N, P and S that are bound in the organic matter structure (Myers, 1995). Organic matter, like some clays, can also hold large amounts of water, which helps nutrients move from soil to plant roots (Mikkuta, 2004).

The content and type of clay mineralogy can play an important role in retaining the added organic carbon (C) and nitrogen (N) in the soil (Christensen, 1992; Cheshire et al., 2000) through physical-chemical stabilization and formation of soil aggregates (Krull et al., 2003). Specific surface area (SSA) and CEC of clay minerals have been shown to be positively related with C and N contents of soils (Jindaluang et al., 2010). Among phyllosilicates, smectites in most studies have been shown to be more intimately associated with retaining and increasing SOM than the other clay minerals (Wattel-Koekkoek et al. 2003), mainly due to their high SSA and CEC (Kaiser and Guggenberger 2003).

Wattel-Koekkoek et al. (2003) defines clay-associated organic matter as all OM present in the clay-size separate, both free and bound. Wattel-Koekkoek et al. (2001) showed that organic matter associated with kaolinite was to a large extent free or bound to alluminium-hydroxide surface, and that smectitic clay minerals preferentially bind organic matter through cationic bridges. Furthermore, it was found that organic matter associated with kaolinite was rich in polysaccharide products, whereas smectite-associated SOM contained more aromatic compounds of many kinds (Wattel-Koekkoek et al., 2001). These differences suggest there is a difference in the dynamics of the organic matter between the two clay minerals, and these clay minerals were chosen as they are the most common in soils.

Soils dominated by most 2:1 clay minerals especially smectites, will therefore increase organic matter retention and decomposition than soil dominated by 1:1 clay minerals. Addition of organic materials on soils dominated by 1:1 clay minerals is advisable to improve the soil's conditions for plant growth.

#### **4.2. Nutrient availability**

Clay minerals are increasingly recognized as an important fraction in soils influencing the nutrient retention capacity and their mobility in specific environments (Boonfueng et al., 2005; Tucker, 1999). The magnitude of the contribution of clay minerals to soil CEC, buffer capacity, cation fixation, and various chemical properties depends upon the nature and amount of the various mineral species present (Pal, 2000). Clay minerals are also extremely important in soil as they provide a mechanism for retaining essential nutrients through ion exchange therefore enhancing soil fertility (Dixon and Schulze, 2002), and they also buffer the soil against rapid changes in acidity or alkalinity and help create soil structure (Wilson, 1999).

Majority of clay minerals have exchangeable cations (Pal et al., 2000). These cations generally are held on the surface of the clay and are not strongly held (Pal et al., 2000), and they can be exchanged for other cations in an equilibrium process. Exchange reactions result in retention of certain plant nutrients in a plant available form in soils; control and buffer soil pH (acidity); and modify the chemical composition of water as it passes through soil (Bergaya and Vayer, 1997). They are usually rapid, reversible and stoichiometric (Rowell, 1994). Different cations in soils are adsorbed more or less easily than others and the tightness with which the soil holds cations varies (Brady and Weil, 1999); it is greatest for hydrogen and aluminum cations and decreases for other cations in the following order:  $Al > H > Ca > Mg > K > Na$ . It is not just the total number of a particular nutrient ion adsorbed in the substrate which determines its availability to plants, but also the fraction of the CEC occupied by that ion. CEC varies according to the type of clay mineral whereby it is usually highest in highly weathered clay minerals such as smectite, lowest in heavily weathered clay minerals such as kaolinite and slightly higher in the less weathered illite, (Bergaya and Vayer, 1997).

The existence of kaolinite as the secondary mineral may have implications with regards to the agricultural potential of the land mainly because of its low CEC, (Ekosse et al., 2011). Higher CEC implies the reduced leaching of nutrients even ion fertilizer application. However, it may also mean retention of contaminants. The CEC can also result in the adsorption of organic compounds if they are charged. Since different soil components hold the various cations with differing tenacities, the presence of certain nutrient ions would therefore limit the availability of others due to differences in attractive forces.

#### **4.3. Fixation of nutrients**

For plant growth and development, 16 mineral elements are essential which are macronutrients [i.e. Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg) and Sulphur (S)]; micronutrients [i.e. Chlorine (Cl), Cobalt (Co), Copper (Cu), Iron (Fe), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Zinc (Zn)] and additional



nutrients [i.e. Carbon (C) Hydrogen (H) Oxygen (O)] (Ronen, 2007). Growing plants have three sources from which they get these necessary nutrients: air, water and soil (Ronen, 2007). These mineral nutrients are available to the plant both in ionic and molecular forms (Scoones and Toulhim, 1998). The nitrate ion can be superior for use by most plants under many varied soil condition such as strongly alkaline, strongly acidic, water logged or dry regions. Phosphorus is the second most important plant nutrient next to N for plant growth and development. The trend for major nutrients in the soil for plant growth is in this order (Uchida and Silva, 2000):  $N > P > K$  and availability of these nutrients in soils depends on the clay mineralogy.

The 1:1 type clays (kaolinite) have a greater P fixing capacity than the 2:1 type clays (montmorillonite, Illite, vermiculite) (Kahr and Madseni, 1995). High temperatures and high rainfall also increase the amount of iron and aluminium oxides in the soil which contributes greatly to the fixation of phosphorus added to these soils (Van der Merwe et al. 2002). Nitrogen ( $N_2$ ) exists in many forms in soil either as organic nitrogen which exists in a reduced form as amine groups or inorganic nitrogen which exists dominantly as ammonium ( $NH_4^+$ ) or nitrate ( $NO_3^-$ ) (Brady and Weil, 1999). Soils vary greatly in their ability to fix  $NH_4^+$  ions depending on their content clay mineralogy (Mamo et al., 1993). Ammonium is generally held in soils as an exchangeable cation, but it can be fixed in soils which contain 2:1 clay minerals such as vermiculite and smectites (Brady and Weil, 1999).

Fixation involves the entrapment  $NH_4^+$  and  $K^+$  ions within the interlayer of the 2:1 type clay minerals (Kiliç, 1999). The equilibrium for soil with fixed  $NH_4^+$  ions is based on a scheme for  $K^+$ :  $(NH_4+K) \leftrightarrow (NH_4+K) \leftrightarrow (NH_4+K)$ . In this scheme the intermediate  $NH_4^+$  (or  $K^+$ ) ions probably occupy interlayer sites close to the edge of the clay crystal either as exchangeable with  $H^+$  or  $K^+$  or recently fixed from fertilizer sources. The concentration of  $K^+$  ions in the soil solution and in the exchange sites is therefore an important factor regulating rates of  $NH_4^+$  fixation and release. If plants take in  $NH_4^+$  from exchange sites, more will be released slowly from fixed positions and become available to plants.  $NH_4^+$  fixation can therefore be viewed as a storehouse of N which helps to buffer changes. These 2:1 clays seem to be the best substrate for plant nutrition and thereby attributing positively to plant growth.

#### 4.4. Soil structure

Soil structure refers to the arrangement of soil particles into aggregates (Six *et al.*, 2000) and is affected by biological activities, organic matter, and cultivation practices (Rowell, 1994). It is also influenced by two factors namely dispersion and flocculation as far as clay minerals are concerned (Parker & Rae, 1998). Dispersion is the breakdown of clay micro-aggregates on wetting, into single particles that are very light (Parker & Rae, 1998). Dispersion occurs as a result of the net electrical charge on the clay causing the particles to repel each other (Christidis and Eberl, 2003). A dispersed condition results in the disruption of soil structure and production of a "massive" condition, with loss of the desired soil structure, reduced soil space, decreased aeration, and restricted water movement (Parker & Rae, 1998).

Flocculation is the clumping together of individual particles into small clumps or floccules (Parker & Rae, 1998). Flocculation results from the neutralization of the net electrical charge on a clay (Mitchell, 1993). It promotes the formation of stable aggregates and of a favorable soil structure (Mitchell, 1993). The charge or valence of the adsorbed ions and the ionic strength of the soil solution are two of the most important factors determining dispersion/flocculation of soil clays (Denef *et al.*, 2002).

Clay dispersion in soil has been observed to increase with the addition of organic matter and with an increase in the sodium adsorption ratio in the presence of humic substances and thereby destroying friability and tilth (Gu and Doner, 1993). Incorporation of gypsum (calcium sulfate) in clayey soils with increased sodium adsorption ratio could provide soluble calcium that can replace the adsorbed sodium. Zhang *et al.* (1991) reported that Na-humate tends to disperse smectite particles, whereas Frenkel *et al.* (1992) observed that the critical flocculation concentration of kaolinite is ten times higher than that of smectite following the addition of about 1% humic acid equivalent.

Smectitic clays are found to be more dispersible than kaolinitic clays (Goldberg and Glaubig, 1987; Stern *et al.*, 1991), thus kaolinitic soils have the greatest aggregate stability than montmorillonitic soils. The greater dispersivity of montmorillonite compared with that of kaolinite decreases the aggregate stability of soils. Six *et al.* (2000) indicated that free oxides and kaolinite clay minerals are important factors for the stability of soil aggregates. Swelling smectite and vermiculite clays could therefore have dispersivity effects on soil structure, whereas kaolinite could have a positive effect on structure due to its low swelling capacity.

#### 4.5. Water holding capacity

Water holding capacity refers to the quantity of water that the soil is capable of storing for use by plants (Brady and Weil, 1999). Soil water is held in, and flows through pore spaces in soils. The sheets of the clay crystal are tied firmly together, but water is still able to penetrate between them (Mitchell, 1993). The ability of the soil to provide



water for plants is an important fertility characteristic (RCEP, 1996). Clay reacts with water in different ways, depending on the type of clay, the chemical and organic matter associated with it and the management applied to the soil (RCEP, 1996). Soils with high clay content have a lot more space to store water than those which are mostly sand (Mitchell, 1993). Clays store large amounts of water, but because they have high wilting points, they need significant rain to be able to supply water to plants (Parker and Rae, 1998).

Although 2:1 clay minerals have the ability to absorb more water in the soil, because of their large surface areas, water movement may be impeded due to soil compaction resulting to water-logged conditions. Water-logged soils due to higher clay content have very little amount of air and under such conditions roots are subjected to anaerobic conditions and the absorption of minerals is drastically affected resulting in poor plant growth (Brady and Weil, 1999). As mineral nutrients absorption requires energy, poor soil aeration would affect the ability of roots to absorb those minerals in adequate quantities.

#### **4.6. Root penetration and growth**

Clay reacts with water in different ways, depending on the type of clay mineral, the chemical and organic matter associated with it and the management applied to the soil (Delvaux et al., 1990). Clay swells when wet because water enters between the sheets of the crystal (Delvaux et al., 1990), conversely, when it dries out it shrinks. In some soils the effect of shrinkage could be seen as large cracks in the ground (Parker and Rae, 1998), which affects the plant roots as it impedes nutrients uptake from soil and breaks roots. Clays with negatively charged basal plates attracts cations, which are surrounded by water (Velde, 1995). As clays dry, the plates are attracted by the positive charges between their layers, which are stronger due to the loss of water, thereby causing soil compaction (Brady and Weil 1999). Plant roots cannot penetrate compacted soil as freely as they would in non-compacted soil, which limits their access to water and nutrients present in sub-soil and inhibits their growth (Hagan *et al.*, 2010). Compacted soil requires more frequent applications of irrigation and fertilizer to sustain plant growth, which can increase runoff and nutrient levels in runoff (Gregory *et al.*, 2006).

Generally, soils inhibited by 2:1 clay minerals because of their shrink-swell potential, are hard when dry and sticky when wet, as a result, they only have a limited range of moisture content suitable for cultivation (Hassett & Banwart, 1992). In clay soils the ability to swell and shrink in response to fluctuation in water addition and removal is vital to the active generation of the visible macrostructure, in which soil aggregates are bounded by cracks and channels that conduct excess water and allow air and roots to penetrate into the subsoil (Delvaux et al., 1990).

### **5. Implications of clay minerals in soil fertility**

The properties of the inorganic fraction in soil holds the key to many processes related to soil fertility including the soils' ability to hold and release nutrients in plant available form (Asadu, 2000). The influence of common clay minerals such as kaolinite (Zhou and Gunter, 1992), smectite (Jongmans et al., 1998), and illite on soil properties (Asadu et al., 1997) has been studied in details (Post and Borer, 2002). The influence of clay minerals on soil fertility could be positive and negative or both.

The existence of kaolinite as the secondary mineral may. Most of the 1:1 type minerals are considered to exhibit the properties of low activity clays (Van der Merwe et al. 2002). Low activity clays are more highly weathered due to their lesser surface area as they have a lower capacity to retain and supply nutrients (Kahr and Madseni, 1995). Soils predominated by these clay mineral types are well drained, where total hydrolysis results in a complete loss of silica and cations (Van der Merwe et al. 2002). Usually soils dominated by 1:1 clay minerals have implications with regards to the agricultural potential of the land mainly because of their low CEC (Ekosse et al., 2011) and are considered to be poor mediums for plant growth (Van der Merwe et al. 2002; Brady and Weil, 1999). Since these soil clay minerals are not highly fertile would perform better in agriculture if the soil is carefully managed and necessary nutrients and organic materials are added to improve the soil conditions and thereby preventing leaching of essential soil nutrients.

Most of the 2:1 type minerals exhibit the properties of high activity clays (Van der Merwe et al., 2002) and are mostly considered to be good mediums for plant growth. Generally, soils with large amounts of high activity clays are not highly weathered (Van der Merwe et al. 2002). High activity clays have a high CEC, due to their large surface area (Brady and Weil, 1999). This indicate that 2:1 clays have a great capacity to retain and supply large quantities of nutrients, such as Ca, Mg, K, and NH<sub>4</sub>, as a result, and they tend to produce highly fertile soils (Brady and Weil, 1999). Although 2:1 clays are mostly known to influence soil conditions positively, it could also influence soil negatively, for instance in a situation where water and nutrients are retained but not available for plant uptake, because of the compact soil structure. Their water holding capacity is very efficient compared to kaolinitic soils due to their ability to expand. However their strong plasticity and stickiness when wet may create mechanical problems during cultivation, making



the soils difficult to till. Addition of organic materials in this condition could therefore be added to improve the soil structure or soil conditions for the betterment of plant growth.

## 6. Research priorities

Additional information on the specific clay minerals and their interaction with soil types and environmental conditions to promote sustainable agriculture is needed to allow identification of more effective management practices. Since clay minerals impacts water retention capacity and nutrient retention and uptake, it is therefore important to develop improved practices for the cautious use of agricultural amendments to maximize their effectiveness while minimizing unintended impacts. More research is therefore needed to establish quantitative relationships between clay mineralogy and agricultural soils.

## 7. Conclusion

A number of studies for soil clays and clay minerals (Ransom et al., 1998; Ekosse et al., 2011; Brady and Weil, 1999; Van der Merwe et al., 2002 and Tucker, 1999) have shown that soil clays and clay minerals influence agricultural land use, soil fertility and soil productivity. Clay minerals therefore contributes many benefits to the soil fertility as they increase the soil's CEC, enhances water holding capacity, provides elasticity, acts as a binding agent for the non clay components, and reduce soil nutrient loss through leaching. A good agricultural soil is therefore one which is dominated by high-activity clays such as smectites, montmorillonites and other 2:1 clay minerals, when other growth factors such as light, water, temperature, and physical conditions of soils are favorable.

## References

- Asadu C.L.A. (2000). Land Use and Soil Management Situation in Nigeria. 20<sup>th</sup> International Short Course on Soil Management at the University of Technology: Dresden, Germany, Sept 7–28, 2000.
- Barrow N.J. (1999). The four laws of soil chemistry: the Leeper lecture 1998. *Australian Journal of Soil Research* 37, 787–829.
- Beckett P.H.T. (1995). Definition of Clay and Clay Minerals: Journal Report of the AIPEA Nomenclature and CMS Nomenclature Committees.
- Bergaya F. and Vayer M. (1997). “Cation Exchange Capacity”: Measurement by adsorption of copper ethylenediamine complex. *Applied Clay Science* 12, 275-280.
- Boonfueng T., Axe L. and Xu Y. (2005). Properties and structure of manganese oxide-coated clay. *Journal of Colloid and Interface Science* 281(1), 80-92.
- Brady N. C. and Weil R. R. (2004). *Elements of the nature and properties of soils*, Upper Saddle River, NJ: Prentice Hall. 13<sup>th</sup> editions.
- Brady N.C. and Weil R.R. (1999). *The Nature and Properties of Soil*. New Jersey, 12<sup>th</sup> edn. Prentice-Hall Inc., p. 881.
- Brigatti M.F., Campana G., Medici L., Poppi L. (1996). The influence of layer charge on Zn<sup>2+</sup> and Pb<sup>2+</sup> sorption by smectites. *Clay Minerals* 31, 477–484.
- Cheshire M.V., Fraser A.R., Hillier S., Dumat C., Staunton S. (2000) The interactions between soil organic matter and soil clay minerals by selective removal and controlled addition of organic matter. *European Journal of Soil Science* 51, 497-509.
- Christensen B.T. (1992). Physical fractionation of soil and organic matter in primary particle size and density separates. *Advances in Soil Science* 20, pp. 1–90.
- Christidis G. and Eberl D.D. (2003) Determination of layercharge characteristics of smectites. *Clays and Clay Minerals* 51, 644-655.
- Delvaux B., Herbillon A.J., Dufey J.E., Vielvoye L. (1990). Surface properties and clay mineralogy of hydrated halloysitic soil clays. Existence of interlayer K<sup>+</sup> specific sites. *Clay Minerals* 25, 129–139.
- Denef K., Six J., Merckx R. and Pautian K. (2002). Short-term effects of biological and physical forces on aggregate formation in soils aggregates with different clay mineralogy. *Plant Soil* 246, 185–200.
- Dixon J. B. and Schulze D. G. (ed.). (2002). *Soil Mineralogy with Environmental Applications*, no. 7. Soil Science Society of America Journal, Madison, WI. Hardback, 866.
- Eghball B. (2002). Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. *Agronomy Journal* 94, 128-135.
- Ekosse G.E., Mwitondi K.S. and Seabi F.T. (2011). Graphical visualization and domain partitioning of minerals in clay fraction of soils from Capricorn District, South Africa. *African Journal of Agricultural Soil Research* 6(2), 467-475.
- Foley N.K. (1999). Environmental characteristics of clays and clay mineral deposits.



- USGS Information Handout, September 1999. URL:<http://minerals.er.usgs.gov/minerals/pubs/commodity/>
- Foth H.D. and Ellis B.G. (1997). *Soil Fertility*. 2nd Ed. CRC Press. Boca Raton, Florida. Pp. 290.
- Frenkel H., Fey M.V., Levy G.J. (1992). Organic and Inorganic Anion Effects on Reference and Soil Clay Critical Flocculation Concentration. *Soil Science Society of America Journal* 56, 1762–1766.
- Goldberg S. and Glaubig R.A. (1987). Effect of saturation cation, pH, and aluminum and iron oxide on the flocculation of kaolinite and montmorillonite. *Clays Clay Minerals* 35, 220-227.
- Gregory J. H., Dukes M. D., Jones P. H., and Miller G. L. (2006). Effect of urban soil compaction on infiltration rate. *Journal of Soil and Water Conservation*, 61, 117–124
- Gu B. and Doner H.E. (1993). Dispersion and Aggregation of Soils as Influenced by Organic and Inorganic Polymers. *Soil Science Society of America Journal* 57, 709–716.
- Guggenheim S. and Martin R.T. (1995). Definition of Clay and Clay Mineral: Journal Report of the AIPEA Nomenclature and CMS Nomenclature Committees.
- Gruhn P., Goletti F., Yudelman M. (2000). Integrated nutrient management, soil fertility, and sustainable agriculture: Current issues and future challenges. A 2020 vision for Food, Agriculture and the Environment. 2020 Brief, September 2000. International Food Policy Research Institute, Washington, D.C. 20006-1002, USA.
- Hassett J.J. and Banwart W.L. (1992). *Soils and their Environment*. Prentice Hall, Englewood Cliffs, New Jersey. pp. viii + 424. Book ISBN0-13-484049-6
- Hagan D. L., Dobbs C. and Escobedo F. (2010). Florida's urban soils: Underfoot yet overlooked. Florida Cooperative Extension Service, University of Florida, Gainesville.
- Havlin J.L., Tisdale S.L., Beaton J.D. and Nelson W.L. (2005). *Soil Fertility and Fertilizers*. Pearson Education, Inc., Upper Saddle River.
- Hillier S. (1995). Erosion, sedimentation and sedimentary origin of clays, in Velde, B., ed., *Origin and mineralogy of clays*: New York, Springer-Verlag, pp. 162-219.
- Jindaluang W., Kheoruenromne I., Suddhiprakarn A., Singh B.P. and Singh B. (2010). Relationships between mineralogical properties and carbon and nitrogen retention in upland soils of Thailand. 2010 19th World Congress of Soil Science, Soil Solutions for a Changing World 1 – 6 August 2010, Brisbane, Australia.
- Jongmans A.G., Pulleman M.M. and Marinissen J.C.Y. (2001). Soil structure and earthworm activity in a marine silt loam under pasture versus arable land, *Biological Fertility of Soils*, 33, 279–285.
- Joussein E., Petit S. and Churchman J. (2005). *Clay Minerals*, Dec 2005, 383-426.
- Kiliç K., Derici M. R. and Saltali K. (1999). The Ammonium Fixation in Great Soil Groups of Tokat Region and Some Factors Affecting The Fixation: I. The Affect of Potassium on Ammonium Fixation. *Turkish Journal of Agriculture and Forestry* 23, 673-678.
- Kahr G. and Madseni F.T. (1995). Determination of the Cation Exchange Capacity and Surface area of bentonite, illite and kaolinite by methylene blue adsorption. *Applied Clay Science* 9, 327-336.
- Kaiser K. and Guggenberger G. (2003) Minerals surfaces and organic matter. *European Journal of Soil Science* 54, 219-236.
- Krull E.S., Baldock J.A., Skjemstad J.O. (2003) Importance of mechanisms and processes of the stabilisation of soil organic matter for modelling carbon turnover. *Functional Plant Biology* 30, 207-222.
- Leinweber P. and Schulten H.R. (2000). New insights into organic–mineral particles: composition, properties and models of molecular structure. *Biological Fertility of Soils* 30, 399–432
- Landon J.R. ed. (1991). *Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics*; Longman Scientific and Ann Arbor Press, Chelsea, pp. 177/196.
- Mamo M., Taylor R.W., Shuford J.W. (1993). Ammonium Fixation by Soil and Pure Clay Minerals. *Communications in Soil Science and Plant Analysis* 24, 11-12, 1115-1126.
- Mathe V., Meunier A. and Leveque F. (2007). Anthropic acceleration of a natural clay mineral reaction in marshland soils (Atlantic Coast, France), *Clay Minerals* 42 , 1–12.
- Mitchell J.K. (1993). *Fundamentals of Soil Behavior*, 2nd edition, John Wiley & Sons (Chapter 3).
- Mikutta C., Lang F., Kaupenjohann M. (2004). Soil organic matter clogs mineral pores: evidence from <sup>1</sup>H-NMR and N<sub>2</sub> adsorption. *Soil Science Society of America Journal* 68, 1853–1862.
- Myers R.J.K. (1995). Modelling of soil organic matter dynamics. In R.D.B. Lefroy et al. (ed.) *Proc. of a Workshop on Soil Organic Matter Management for Sustainable Agriculture*, Ubon, Thailand. 24-26 Aug. 1994. ACIAR Proc. 56 pp. 140-148. ACIAR, Canberra, Australia.
- Olis A.C., Malla P.B., and Douglas L.A. (1990). The rapid estimation of the layer change 2:1 expanding clays from a single Alkyl ammonium ion expansion. *Clay Minerals* 25, 39-50.



- Pal D.K., Bhattacharyya T., Deshpande S.B., Sarma V.A.K. and Velayutham M. (2000). Significance of Minerals in Soil Environment of India. NBSS Review Series 1, NBSS and LUP, Nagpur, 68.
- Parfitt R.L., Theng B.K.G., Whitton J.S., Shepherd T.G. (1997). Effects of clay minerals and land use on organic matter pools. *Geoderma* 75, 1–12.
- Parker A., Rae J.E. (eds.). (1998). *Environmental Interactions of Clays*. Berlin, New York, Springer.
- Peinemann N., Amioti N.M., Zalba P., and Villamil M.B. (2000). Effect of clay minerals and organic matter on the cation exchange capacity of silt fraction. *Journal of Plant Nutrition and Soil Science* 163, 47–52.
- Post J.L. and Borer L. (2002). Physical properties of selected illites, beidellites and mixed-layer illite-beidellites from southwestern Idaho, and their infrared spectra. *Applied Clay Science* 22, 77–91.
- Ransom B., Dongseon K., Kastner M., and Wainwright S. (1998) Organic matter preservation on continental slopes: Importance of mineralogy and surface area. *Geochimica et Cosmochimica Acta* 62,1329-1345.
- Ronen E. (2007). Micro elements in agriculture. *Practical Hydroponics & Greenhouses*. July/August, 39.
- Rowell D.L. (1994). *Soil Science: Methods and applications*, London: Longman. A detailed discussion of soil physical and chemical properties
- Royal Commission on Environmental Pollution (RCEP). (1996). *Sustainable Use of Soil*, London: HMSO. A select committee report on the impact of development on soils, on soils in relation to land use, and on soil pollution. Up-to-date, with many examples from the United Kingdom.
- Scoones I., and Toulmin C. (1998). Soil nutrient balances: What use for policy? In E.M.A. Smaling (ed.) *Nutrient flows and balances as indicators of productivity and sustainability in sub-Saharan African agro-ecosystems*. *Agricultural Ecosystem and Environment*, (in press).
- Six J., Elliott E.T. and Paustian K. (2000). Soil structure and soil organic matter: II. A normalized stability index and the effect of mineralogy. *Soil Science Society of America Journal* 64,1042–104.
- Stern R., Ben-Hur M. and Shainberg I. (1991). Clay mineralogy on rain infiltration, seal formation and soil losses. *Soil Science* 152: 455-462.
- Tucker M. R. (1999). *Clay Minerals: Their Importance and Function in Soils*. *Soil Fertility Note* 13, February 1999.
- Uchida R. and Silva J. A., (eds). (2000). *Plant Nutrient Management in Hawaii's Soils, Approaches for Tropical and Subtropical Agriculture*. College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa.
- Van der Merwe G.M.E., Laker M.C., and Buhman C. (2002). Clay mineral association in melanic soils of South Africa. *Australian Journal of Soil Resources* 40, 115–126.
- Velde B. (2001). Clay minerals in the agricultural surface soils in the Central United States. *Clay Minerals* 36, 277–294
- Velde B. (1995). Origin and mineralogy of clays. *Clays and the environment*. New York Springer.
- Velde B., Goffé B. and Hoellard A. (2003). Evolution of clay minerals in a chronosequence of poldered sediments under the influence of a natural pasture development. *Clays and Clay Minerals* 51 (2), 205–217.
- Visser S.A., Caillier M. (1988). Observation on the Dispersion and Aggregation of Clays by Humic Substances. I. Dispersive Effects of Humic Acids. *Geoderma* 42, 331–337.
- Wattel-Koekkoek E.J.W. (2001). Amount and composition of clay-associated soil organic matter in a range of kaolinitic and smectitic soils. *Geoderma* 99, 27–49.
- Wattel-Koekkoek E.J.W., Buurman P., van der Plicht J., Wattel E. and van Breemen N. (2003) Mean residence time of soil organic matter associated with kaolinite and smectite. *European Journal of Soil Science* 54, 269-278.
- Wilson M. J. (1999). The Origin and Formation of Clay Minerals in Soils: Past Present and Future Perspectives *Clay Minerals* 34, 7-25.
- Zhang Y., Gan H., Low P.F. (1991). Effect of Sodium Humate on the Rheological Characteristics of Montmorillonite Suspensions. *Soil Science Society of America Journal* 55, 989–993.
- Zhou Z. and Gunter W. D. (1992). Nature of the surface charge of kaolinite. *Clays and Clay Minerals* 40 (3), 365-368.