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MINERALOGICAL AND PARTICULATE MORPHOLOGICAL CHARACTERIZATION OF GEOPHAGIC CLAYEY SOILS FROM BOTSWANA

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ABSTRACT. This study focused on determining the minerals composition and particle morphology of geophagic clayey soils from Botswana in order to infer on how they could influence human health. Six representative geophagic clayey soils from Botswana were mineralogically characterized using X-ray powder diffractometry (XRPD), optical microscopy, and environmental scanning electron microscopy (ESEM). Results of identified mineral phases revealed quartz (SiO_2) as the most dominant in all samples constituting close to 70 wt %; followed by goethite (FeO.OH) having a mean concentration of 9 wt%, and kaolinite ($Al_2Si_2O_5(OH)_4$) with a mean concentration of 8 wt%. Other minerals present were smectite ($((Na,Ca)(Al,Mg)_6(Si_4O_{10})_3(OH)_{6-n}(H_2O))$), mica ($(AB_{2-3}(Al,Si)Si_3O_{10})(F,OH)_2)$), feldspar ($(Na/K(AlSi_3O_8))$) and hematite ($(Fe_2O_3)$). The quartz particles were generally coarse; and angular to very angular in morphology. Due to ions present in goethite, kaolinite, and smectite, these minerals impact positively on properties of geophagic clayey soils and could possibly influence human health when consumed. The quartz particles could negatively affect dental enamel as a result of mastication; and cause abrasion of the walls of the gastro-intestinal tract which may lead to rupturing. Although the studied clayey soils could have potential to provide medicinal benefits to the consumer, there is need for beneficiation exercise to be conducted to reduce the coarse angular particles contained in them. It is therefore necessary for constructive efforts to be directed at beneficiating geophagic materials which will render them safe for human consumption.

KEY WORDS: Beneficiation, Geophagia, Kaolinite, Quartz, X-Ray powder diffractometry

INTRODUCTION

Geophagia or geophagy, classified as a form of pica [1] is the habitual wilful consumption of earth (soils and clays) or soil-like substances such as chalk, by humans (human) and animals (enzootic) [2-4]. The word is derived from the Greek words *geo-* (earth) and *phag*-(eat) [5]. Human geophagia has been considered to be a psychiatric disease; culturally sanctioned practice or perhaps a sequel to poverty and famine [6]. It has been related to nutritional, psychological, cultural and medical [7], social [8], taste [8], spiritual, religious, ritual [9] and physiological needs [10]. Homo *habilis* practiced geophagia over two million years ago [11], and there are its recordings about 5500 years back among past civilizations in Africa and Asia [12]. It is widely practiscd in almost all continents [13-17], by people of different cultures, races, ages, and socio-economic groupings [18]. In Southern Africa, various ethnic groups and tribes have different names which geophagic clayey soils are referred to [19].

Geophagic clayey soils are generally composed of kaolin of which kaolinite is the dominant type of mineral [20]. Other clay minerals found in geophagic clayey soils include palygorskite, and montmorillonite (usually from bentonite). Studies on soils eaten by gorillas showed that they contained quartz, atatite, analbite, sanidine, amphibole, ilmenite, limonite, magnetite and halloysite [21]. Clayey soils are made up of aluminium silicate hydroxide and trace elemental constituents [22]. Organic pollutants such as pesticides could also be present in geophagic

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clayey soils. Clayey soils have been reported to be medicinal and could be possible sources for nutrient supplementation [23, 24]. Geophagia has potential benefit as a source of mineral supplementation (especially Fe and Ca) [25, 26]. Kaolin and bentonite are widely used as modern day digestive aids and for detoxification; and attapulgite (mineralogically known as palygorskite) is active ingredient in several anti-diarrhoeal drugs [6, 7]. Beliefs and views generally held about the consumption of clayey soils are that the soils impart a soothing effect on internal and external ulcers; arrests diarrhoea (antiquity till today); reduces nausea and morning sickness in pregnancy (antiquity till today worldwide); a Ca source for foetal development (modern day Ghana/Nigeria); facilitates childbirth and alleviates disorders of menstruation (17^{th} Century Europe) [27]. In South Africa, some geophagic practitioners believe that the eating of the clays enhances the softening of the skin and makes it lighter [6].

Although there may be apparent health benefits in the consumption of geophagic clayey soils, several environmental factors and mode of ingestion without any form of treatment may pose health risks to the individuals. Although some geophagic practitioners prefer eating the clayey soil in baked form which may be necessary for the reduction of bacterial and microbial loads, more often the soils are ingested without any form of treatment. The consumption of geophagic clayey soils could be vehicular to orally-transmitted pathogenic nematodes (*Trichuris, Ascaris* and *Strongyloides species*) from soil [28, 29]. Other major risks associated with geophagia could be micronutrient malnutrition, and micronutrient deficiency of Fe (less with anaemia/Hb), Zn, Cu and Mn, through reduced absorption, even if these nutrients are bioavailable.

Despite the risks associated with the consumption of geophagic clayey soils, the practitioners continue incessantly to indulge in the practice. Though not substantiated, observations by authors and personal communications with vendors and geophagic practitioners were indicative of the consumption of geophagic clayey soils being highly rampant among females in rural dwellings and to a lesser extent, those in urban and peri-urban settings. Studies conducted on geophagic practice in South Africa and Swaziland were reflective of the practice being common, widely distributed, addictive and easily sustained [19, 30]. These observations and findings engineered this initiative study that focused on mineralogical characterization of geophagic clayey soils from Botswana.

EXPERIMENTAL

The representative geophagic clayey soil samples used for this study were purchased from roadside/street vendors in the following different parts of Botswana: Gaborone (24^o 38' 47" S and 25^o 54' 43" E), Kanye (24^o 59' 0" S and 25^o 21' 0" E), Francis town (21^o 10' 0"S and 27^o 31' 0" E), Palapye (22^o 33' 0"S and 27^o 8' 0" E), Selebi Phikwe (21^o 57' 0" S and 27^o 37' 0" E). Samples S-60 and S-64 were from Gaborone, sample S-66 was from Kanye, sample S-68 was obtained from Francistown, sample S-69 was from Palapye, and sample S-70 was obtained from Selebi Phikwe. The obtained samples were first air-dried for 24 hours prior to conducting the analyses. Four main types of analyses were performed on the samples, and these were: Clayey soil color; X-ray powder diffractometry (XRD) tests for minerals identification and minerals quantification; optical microscopy for morphology of sand/silt particles; and environmental scanning electron microscopy (ESEM) for morphology of the clay size particles in the geophagic clayey soils.

Clayey soil samples used for color determination were disaggregated using a mortar and pestle. A plastic spatula was used to mount the disaggregated samples on white cardboard sheets provided by the Munsell Color Company Inc., MD 21218, USA. The color descriptions of the samples, which comprised the hue, value/chroma and color was obtained by visually comparing it to those of standard soils recorded in the Munsell Soil Color Book [31]. Its chart was interpreted as follows: hue = color, value = lightness of color, and chroma = purity of color. If a clayey soil is color classified as 10YR7/8, it is by interpretation 10YR = yellow red value on the hue band; 7 = lightness value of the color; and 8 = the level of purity on the chroma.

Samples for XRD analysis were ground into powder form using a mortar and pestle. The samples (in the powder state) were loaded in sample holders and mounted in the Philips PW 3710 XRPD X-ray diffractometer system for qualitative and quantitative identification of mineral phases contained in them. The analysis was conducted on XRPD equipment having a Cu-K_α radiation and a graphite monochromator, set to operate at 40 kV and 45 mA [4]. Samples were scanned at a speed of 1^o 2θ/min; covering a range of 2^o 2θ to 70^o 2θ. The raw data was captured with the aid of a PW 1877 Automated Powder Diffraction (APD) X'PERT Data Collector software package. A Philips X'PERT Graphics & Identify software package was used for qualitative identification and semi quantitative analyses of the minerals from both the data and patterns obtained. The results were compared with data and patterns available in the Mineral Powder Diffraction File data book [32].

Optical microscopy technique was used for descriptive analysis of the non-clay size particles in the clayey soil samples. The process involved the identification of the non-clay size particles and describing their hardness, cleavage, fracture, color, streak, luster, crystal appearance and morphologies. A Leitz Ortholux II Pol-BK petrographic microscope was used for the analyses of the particles. The ESEM analysis centered on morphology and orientation of particles in the geophagic clayey soil samples [26]. The powdered samples were placed on a 3 mm pin type stub with a carbon tab on. The samples were examined in a Philips XL30 Environmental Scanning Electron Microscope (ESEM) in Low Vacuum mode (LVM) to prevent possible morphological changes in the particles due to dehydration in the vacuum. Afterward the samples were gold (Au) coated in an SPI sputter coater and viewed in High Vacuum mode (HVM). The results were also compared with the LVM images to ensure that the shapes of the plates were not deformed due to dehydration in the high vacuum. No significant differences were observed in either mode.

RESULTS AND DISCUSSION

Color of geophagic clayey soils

Color is the first diagnostic parameter used by geophagic practitioners to determine suitability of soil for consumption. It is used to infer on palatability of the geophagic clayey soil. A summary of the color of the geophagic clayey soils from Botswana are presented in Table 1. The colors of the samples were from white (2), light grey (1), yellow (1), and light yellow brown (1) to dark grayish brown (1). According to vendors from whom the samples were bought, geophagic practitioners in the country preferred mostly the white and dark grayish brown clayey soils. Most geophagic clayey soils from South Africa are whitish, grayish or khaki because of kaolin, smectite, and calcite; and others from Swaziland are reddish or yellowish due to hematite and goethite contained in them [33; 34]. These colors obtained for geophagic clayey soils from Botswana are similar to those reported for samples studied from South Africa and Swaziland.

Minerals identification and quantification

The following nine clay and non clay minerals were identified in the samples: quartz, kaolinite, calcite, microcline, smectite, talc, mica, hematite and dolomite. The names of the minerals, their chemical names, and chemical formulae, and main diagnostic peaks used for their identification are given in Table 2. Quartz, kaolinite and mica occurred in all the samples. Quartz was the most dominant mineral ranging from 70 wt% for sample S-69 to 80 wt% for samples S-66 and S-68 identified in the geophagic clayey soil samples (Figure 1). The quantitative abundances of kaolinite in the samples were from 3 wt% for sample S-68 to 12 wt% for sample S-64 (Figure

2). Mica wt % in the samples was from 4 wt% for sample S-64 to 25 wt% for sample S-69 (Figure 3). Feldspar occurring as microcline was present in four of the samples. Its wt % abundance was very low ranging from 2 wt% for sample S-68 to 4 wt% for sample S-69 (Figure 4). Smectite, present in the form of Na montmorillonite, was identified in samples S-66 and S-70; and it was only 2 wt % in each of the two samples. Samples S-60 and S-69 each had 1 wt % of talc; sample S-64 had 16 wt% of hematite, and 5 wt% of sample S-60 consisted of dolomite.

Table 1. Hue, value, chroma and color of analyzed Botswana geophagic clayey soils.

Sample No.	Geophagic clayey samples	
	Hue/value/chroma of sample	Color of samples based on Munsell Soil Color Chart
S-60	2.5Y / 8/1	White
S-64	10YR / 4/2	Dark greyish brown
S-66	7.5YR / 7/1	Light grey
S-68	2.5Y / 6/3	Light yellow brown
S-69	10YR / 7/8	Yellow
S-70	2.5Y / 8/1	White

Table 2. Minerals identified by XRD in geophagic clayey soil samples from Botswana.

Name of mineral	Chemical name	Chemical formula	Main diagnostic peaks (dÅ)
Clay minerals Kaolinite	Aluminum silicate hydroxide	$Al_2Si_2O_5(OH)_4$	7.1, 4.41, 3.56
Smectite (Na montmorillonite)	Hydrated sodium calcium aluminum silicate	$(Na,Ca)(Al,Mg)_6(Si_4O_{10})_3(OH)_{6-n}H_2O$	13.6, 4.46, 2.56
Talc	Magnesium silicate hydroxide	$Mg_3Si_4O_{10}(OH)_2$	9.34, 4.66, 3.11
Mica (muscovite)	Potassium magnesium aluminum silicate hydroxide	$KMgAlSi_4O_{10}(OH)_2$	9.91, 4.50, 2.56
Non-clay minerals			
Quartz	Silicon dioxide	SiO_2	4.25, 3.34, 1.82
Calcite	Calcium carbonate	$CaCO_3$	3.04, 1.91, 1.87
Dolomite	Calcium magnesium carbonate	$CaMg(CO_3)_2$	2.89, 2.19, 1.79
Feldspar (Microcline)	Potassium aluminum silicate	$KAlSi_3O_8$	4.22, 3.26, 3.25
Hematite	Iron oxide	Fe_2O_3	2.70, 2.52, 1.69

Non-clay size minerals characterization

Non-clay size particles for each sample were identified under the microscope. Although hardness, cleavage, fracture, color, streak and luster were used in identifying the minerals, of significance to the study is the mineral hardness. Quartz was the most dominant particle type in all the samples, with a Mohs scale hardness of 7 (Table 3). Within the Mohs scale used to determine hardness of minerals, talc is the softest and diamond the hardest on a scale of 1-10. Quartz, being 7, is therefore very hard in addition to its general chemical inertness. The morphology of the quartz in the samples reflected particles which were generally coarse; and angular to very angular. Close to the hardness of quartz in identified non clay minerals in geophagic clayey soil samples are microcline with a hardness of 6-6.5 and hematite having a hardness of 5.5-6.5. Calcite and dolomite have a hardness of 3 and 4 respectively (Table 3).

Mineral fracturing and cleavage are properties that could be exploited by the digestive system. As cleavage and fracturing occur, the surface area of geophagic clayey soil particles that gets in contact with gastro-intestinal juices equally increases. Quartz, microcline and hematite do not have any distinctive cleavage. Calcite and dolomite have perfect cleavage. The colors of the non clay minerals impact on the color of the geophagic clayey soil. Apart from hematite that is black, the other non clay minerals are white, milky and glassy with some possible color stains due to elemental substation within the mineral crystal structure.

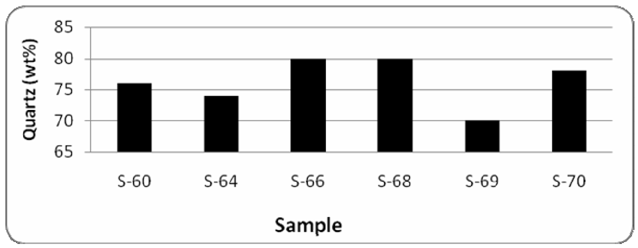

Figure 1. Quantitative distribution of quartz in geophagic clayey samples from Botswana.

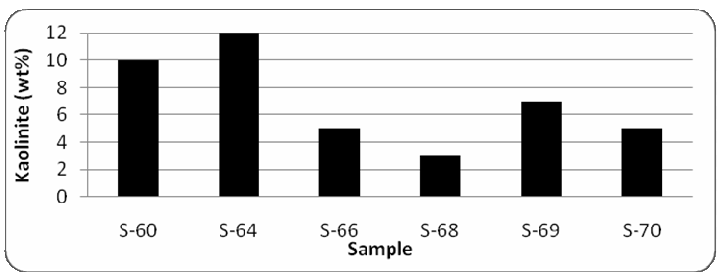

Figure 2. Quantitative distribution of kaolinite in geophagic clayey samples from Botswana.

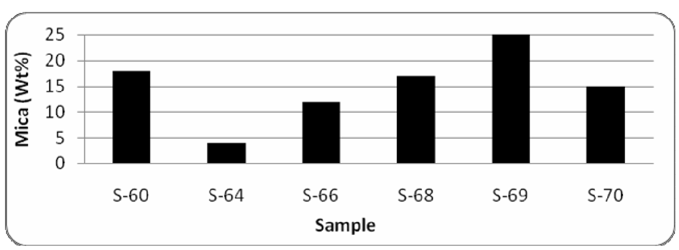

Figure 3. Quantitative distribution of mica in geophagic clayey samples from Botswana.

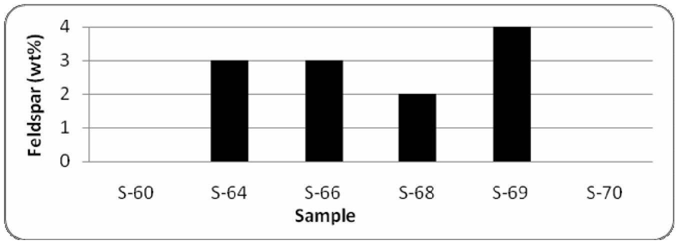

Figure 4. Quantitative distribution of feldspar in geophagic clayey samples from Botswana.

Clay size particle morphology

The morphology of the clay size particles in the geophagic clayey soils was dominated by typical kaolinite morphology. The fine particles of samples S-60, S-66 and S-70 distinctly reflect pseudo-hexagonal platelets of kaolinite (Figure 5). Similar pseudo-hexagonal platelets of kaolinite were observed in the other samples but to a less extent. The smaller particles on the pseudo-hexagonal platelets were smectitic particles. The thin flaky platelets which compacted into unoriented booklets have been a property exploited by pharmaceutical companies in the production of the widely used kaopectate. Pseudo-hexagonal platelets could form coating on the gastro-intestinal (G-I) tract; aiding in the relief of gastric pains and ulcers. Samples S-64 and S-68 had their kaolinite particles embedded in massy swirl-like particles (Figure 6), and flaky plates compacted into a vermiform-like structure. There were rounded bits of particles which could possibly be partially altered microcline scattered between larger particles in samples S-64 and S-68.

Table 3. Descriptive mineralogy of the non clay minerals contained in geophagic clayey soil samples.

Mineral	Hard- ness (Mohs scale)	Cleavage	Fracture	Color	Streak	Lustre	Crystal appearance
Quartz	7	None	Conchoidal	White, milk, glassy, purple	White	Vitreous	Hexagonal
Calcite	3	Perfect	Uneven	Colorless, white	White to yellow	Vitreous to silky	Hexagonal
Dolomite	4	Perfect	--	Colorless or white with yellow or brown tinge	White	Transparent/ translucent	Hexagonal
Hematite	5.5-6.5	None	--	Black	Dark red	Opaque	Hexagonal
Microcline	6 - 6.5	None	Conchoidal to uneven	Variety from white, blue to yellow	Trans parent	Vitreous	Triclinic

Health consequences associated with geophagic clayey soils

Clay usage and applications are related to their physico-chemical and chemical properties and mineralogical compositions [1]. Literature describes some medical conditions commonly associated with geophagia, without necessarily determining any causal relationship between the practice and these morbid conditions [3, 4]. The size, shape and nature of foreign bodies in the G-I tract have been reported to cause intestinal perforation [35]. Mineralogically, all the studied geophagic clayey soil samples contained kaolinite and two of them had smectite. Kaolinitic clays are used as anti-diarrhoeal medicine because of their ability to absorb water from human digestive tract. Smectitic clays are natural intestinal detoxifier having the ability of absorbing toxins from the gastrointestinal tract [36, 37]. Quartz particles in the studied samples were similar to those of other studied geophagic clays [33]. They were very angular and coarse, chemically and mineralogically inert. In the mouth, quartz particles easily damage dental enamel due to its hardness being more than that of the main dental enamel material, hydroxylapatite (a calcium phosphate mineral with a Mohs scale hardness of 5) [34]. Being the most dominant in terms of wt %, quartz in the Botswana samples could destroy dental enamel. Another health risk resulting from the angular coarse quartz particles is the possible abrasive tendencies they may cause in the human gastro-intestinal tract. Many more studies have linked geophagia with other health risks such as increased prevalence of intestinal helminths, especially *Trichuris* and *Ascaris* spp. [38-40].

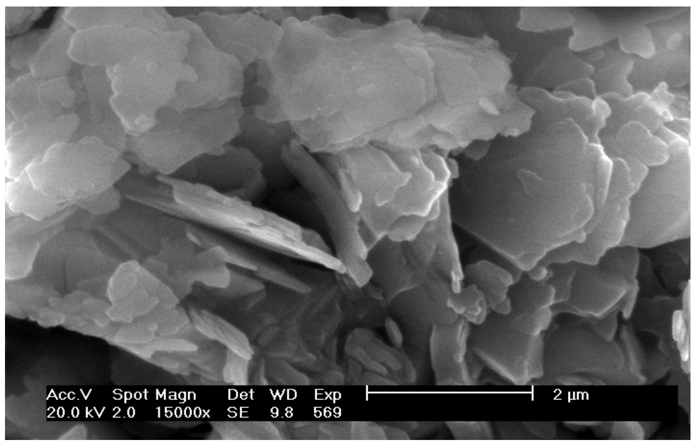

Figure 5. Scanning electron photomicrograph of a representative geophagic clayey soil sample depicting pseudo-hexagonal platelets of kaolinite.

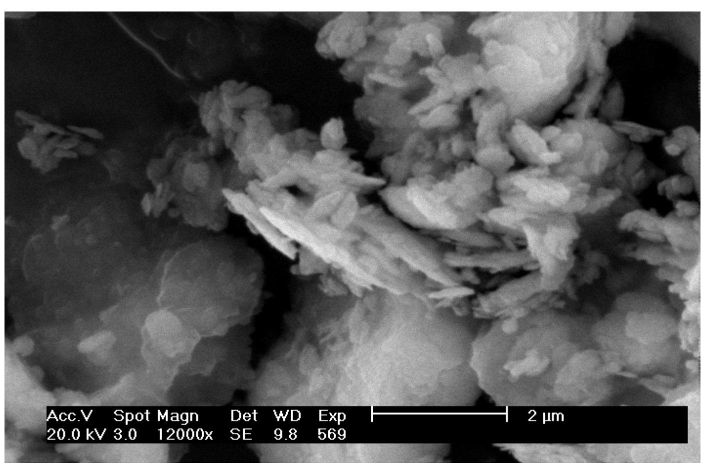

Figure 6. Scanning electron photomicrograph of a representative geophagic clayey soil sample depicting compacted flaky platelets of kaolinite surrounded by massy swirl-like structures.

Isomorphic substitution of ions occurring in octahedral sheets of smectite and kaolinite due to vacant sites promotes clay chemical reactions. Calcium and Mg from dolomite, calcite, smectite and talc; K from feldspar, and Fe from hematite could be supplied from the geophagic clayey soils and absorbed as possible nutritional supplements [41]. Some studies have associated geophagia with mineral and electrolyte, blood (low iron and calcium levels) and iron-deficiency anaemia [42, 43]. There still remain imbalances in the unclear subject, however, whether the low blood iron induces craving for soil, or if geophagia causes low iron status because of the interference of the soil with iron absorption in the blood. Kaolinite and smectite particles are generally very small (< 2 μm in diameter) enabling them to manifest large surface areas over which cations and micro organisms could easily adhere [44]. This property allows kaolinite and smectite particles in the studied geophagic clayey soils from Botswana to create surface coating on the stomach with inferred possible pharmacological implications.

There are grave concerns as well regarding the non-processing of geophagic clayey soils. More often, the material is mined with crude implements that are rusty [33]. These tools pose as sources of contamination of the material. The ingestion of bacteria and microbes, and heavy metals from soils has been mentioned. There is, therefore, the need for geophagic clayey soils to be beneficiated and made safe for human consumption since the habit cannot be eradicated. Geophagia may not be comparable in morbidity and mortality to the various communicable and non-communicable diseases that plague the African continent. However, its insidious toll on the blood iron and hemoglobin levels of populations that might already be burdened by other diseases, poverty and malnutrition makes geophagia a potential public health threat

CONCLUSIONS

This study has focused on the mineralogy and particle morphology of geophagic clayey soils from Botswana, Southern Africa. It established the qualitative and quantitative minerals compositions of the geophagic clayey soils. Quartz, kaolinite, and smectite were dominant minerals contained in the samples, and to a less extent goethite. These minerals because of their chemical compositions (and more specifically elemental constitutions) could be of nutritional significance to the consumers. The ions present in goethite, kaolinite, and smectite impact positively on properties of geophagic clayey soils and could possibly influence human health when consumed. Quartz particles could negatively affect dental enamel due to mastication; and could also cause abrasion of the walls of the gastro-intestinal tract which may lead to rupturing. There is thus a need for beneficiation exercise to be conducted to reduce the coarse angular sandy and silt particles contained in them which are dominantly quartz, even though the studied clayey soils could have potential to provide nutritional and medicinal benefits to the consumers.

Geophagic practice is well rooted among the people in Botswana as well as several other countries in Africa. A strong need for constructive efforts being directed at beneficiating geophagic clayey soils is imperative. The exercise must target the rendering of the geophagic clayey soils safe for human consumption through physical, physico-chemical and microbiological treatments. Further research thrusts should embark on environmental health, hematology, microbiology, nutrition and allied disciplines associated with geophagia.

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