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Chemical characterization of leonardite and its potential use as soil conditioner and plant growth enhancement

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Abstract

Humic substances which are major component of natural organic matter (NOM) play a major role through their impacts on soil fertility (physical, chemical, and biological soil properties) and plant development. Concerns about soil and environmental degradation caused by intensive high-input agriculture stimulated substantial efforts to increase organic matter particularly humic substances in the soils. Leonardite is NOM which contains high amount of humic substances particularly humic acid. Leonardite from various deposits in Thailand was examined as a potential NOM for soil improvement. Chemical compositions of leonardite varied from deposit to deposit. Leonardite from Lee mine contained the highest amount of humic acid (39.19 to 85.05%). Plant nutrients elements contained in all the leonardite samples were quite high (N, K, S, Ca, Mg, Fe, Zn and Mn) except for phosphorus. Characterization of leonardite samples by X-ray diffraction (XRD) and X-ray fluorescence spectrometry (XRF) showed that silica (Si) was the major element. High plant nutrients and humic acid content in leonardite samples indicated its high possible use to improve organic matter, humic acid and some plant nutrient levels in the soils. However, the very low pH values (1.84 to 2.55) and low P content (28.6 to 211.2 mg kg^{-1}) of most leonardite samples should be raised before use. The information obtained from our study would be useful for appropriate use of leonardite in agriculture. In addition, with layer structure, high humic acid and nutrients contents of leonardite, it could be also used as microbial carrier as well as peat. Further investigation should be performed to obtain maximum benefit from this natural organic material.

Keywords: *Leonardite; Plant nutrients; Soil amendment, SEM*

1. Introduction

Soil degradation, a decline in soil health and quality caused by human activities, has been a major global issue for the 21st century. Because of its adverse impact on agricultural productivity, food security, life and environment quality, the year 2015 has been declared the International Year of Soils by the United Nations (UN) [1]. In the past few decades, intensive farming and inappropriate soil practices have brought about soil degradation manifested by the decline in soil organic matter (SOM) and fertility. It is now widely accepted by scientists that SOM depletion is one of the major factors of soil degradation and can be used as soil fertility index. This organic matter has to be replaced in order to maintain fertile soil and reduce soil degradation. Humic substances (well-decomposed and highly stable organic material i.e. humic acid, fulvic acid and humins) constitute an important fraction of soil organic matter, have a positive influence on soil fertility and the physical integrity of soil, and increase the availability of nutrients [2 & 3]. Natural biominerals particularly leonardite have recently become attractive as soil amendments and as sources of humic acid for soil and plant yield improvement. Leonardite is a natural organic material created through a more than billion years-decomposition process [4]. This natural-oxidized material, which contains up to 86 percent humic acids on a moisture-and-ash-free basis, has been given the name “Leonardite” after A. G. Leonard who did much of the early studies on this material [5]. As a convenient and commercial source of humic acids, extensive reserves of leonardite occur virtually all lignite outcrops in several mining areas in Thailand particularly in Mae Moh mine, Lampang Province. The amount of lignite coal in this reserve area is about 1,139 million tons which represents highest volumes of both lignite and leonardite in Thailand. There are other sources of leonardite in the new mining areas such those in Lamphun, Phayao and Krabi Provinces. Leonardite is rich in organic matter (50 to 75%) and its humic acid content could range between 30 to 80% [3]. Humic acid and other humic compounds stimulate soil aggregation, root and shoot development, increase both available plant nutrients and nutrient uptake from soil. Humic and fulvic acids are usually used in agricultural production and are widely known as having agronomic potential [5].

The use of leonardite in agriculture is expanding due to its high content of humic acid. However, information related to its structure, elemental and mineral composition is quite limited. Quality and property of leonardite might vary widely from deposit to deposit. Chemical characterization of leonardite would be useful and might lead to appropriate use as soil conditioner and organic fertilizer. Therefore, this study aims to investigate the chemical properties of leonardite and evaluation of its potential use in agriculture.

2. Materials and Methods

In this study, leonardite from various locations were analyzed for nutrients, organic matter and humic acid contents. The samples were also examined for mineral crystallography by X-ray diffraction (XRD). The major chemical compositions of leonardite were analyzed by X-ray fluorescence spectrometer (XRF). The crystals morphologies of leonardite samples were examined by scanning electron microscope (SEM).

2.1 Description of leonardite samples

The sampling areas were located in several provinces of northern Thailand. The leonardite samples were collected from three locations regarded as different sources of leonardite i.e. Mae Moh (LD1, LD2 and LD3), Chiang Muan (LD4, LD5 and LD6) and Lee (LD7 and LD8) located in Lamphun, Lampang and Phayao Province, respectively. In each location, three spots were chosen for leonardite sampling except for Lee area where only two spots could be sampled.

2.2 Determination of Physical and Chemical properties of leonardite

The leonardite samples were analyzed for nutrient contents; nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn) and manganese (Mn). Some selected samples of leonardite were also analyzed for other characteristics; organic matter content (%OM) and humic acid (%HA) [6 & 7].

2.3 X-ray diffractometry (XRD) and X- Ray Fluorescence Spectrometry (XRF)

Base on chemical properties obtained from 2.2, only five leonardite samples were selected for further investigation. The five samples included LD 2-3 (Mae Moh 2), LD3-2 (Mae Moh 3), LD4-2 (Chiang Muan 2), LD8-1 (Lee, Lamphun) and LD8-3 (Lee, Lamphun).
X-ray diffraction analysis was carried out on a Bruker D 8-Advance diffractometer in order to identify the crystalline phases of the selected leonardite samples. The major chemical compositions of leonardite were analyzed by X-ray fluorescence spectrometer (XRF).

2.4 Scanning electron microscope (SEM)

The crystals morphologies of selected leonardite samples were examined by scanning electron microscope (SEM). The determination was performed using JEOL (model JSM-5910LV) scanning electron microscope (SEM) at EMR Sc CMU (Electron Microscopy Research and Service Center, Chiang Mai University).

3. Results and Discussion

3.1 Chemical properties of leonardite

Because leonardite is a naturally mined material, the results from this study showed that the chemical properties of leonardite were slightly different in the same deposit but highly different from deposit to deposit. The lowest pH values were found in LD8 with the average value of 1.93. The pH values of LD7, LD1, LD2 and LD3 were also quite low (2.38 to 2.51) (Table 1). These pH values of leonardite from Lee and Mae Moh were considered as extremely acid which are common features for leonardite. Natural organic deposit peat and leonardite are completely decomposed plant residues formed under anaerobic conditions which lead to organic acid production thus the low pH of the materials. The accumulation of organic matter in cultivated soil can also lead to soil acidification, the decrease in pH can be extended to a depth of >30 cm [8]. Pochadom et al. (2013)

[9] found that the pH of leonardite from lignite mine was around 4, which is strongly acidic. In contrast to other deposit, the pH values of leonardite from Chiang Muan; LD4, LD5 and LD6 were only moderately or slightly acid (5.61 to 6.20). This might due to the fact that leonardite was already contaminated with ground soil in the collected area. The beneficial effects of leonardite applied to acid soils might not be expected if the pH of leonardite is not improved before application. In contrast, in alkali soils, leonardite might improve the fertility of the soils and help to lower the pH of alkali soil to a level suitable to plant growth.

In general, leonardite contains high amount of organic matter (%OM), about half or more of its weight. Several studies have shown that the OM values in leonardite range from 43.60 to 54.5% [10 & 11]. In the present study, leonardite samples from Lee mine contained the highest amount of OM (48.66 to 61.02%) (Table 1). On the average %OM of leonardite from Chiang Maun was lowest among all the samples (≈ 19.2%) which confirmed the samples were contaminated with soils particularly LD5 and LD6. Among natural organic materials, leonardite contains very high humic and fulvic acids (40 to 85%) compared to that of peat (10 to 20%) and compost (2 to 5%). Our results showed that leonardite from Mae Moh (LD1, LD2 and LD3) and Lee mine (LD7 and LD8) contained quite high amount of humic acid (34.73 to 61.58 and 39.19 to 85.05%, respectively). Humus (humic acid and fulvic acid) in organic material acts as a significant reserve of plant nutrients and improves soil structure and water holding capacity. However, organic matter content in most agricultural soil under modern agriculture is quite low (<1%) thus very low humus content [12]. Organic matter depletion results in a decrease in crop productivity. Therefore, natural high humic acid material like leonardite could be used to improve organic matter, humic acid and some plant nutrient levels in the soils.

Table 1 Some chemical properties of leonardite samples

Leonardite sample	pH	Total Sulfur (%)	Organic matter (%)	Humic acid (%)
LD1-1	2.51	5.18	30.76	58.55
LD1-2	2.54	5.25	30.45	59.53
LD1-3	2.48	5.14	31.27	55.80
Mean LD1	2.51±0.03	5.19±0.06	30.82±0.41	57.96±1.93
LD2-1	2.38	6.36	22.30	36.65
LD2-2	2.38	5.50	22.87	34.73
LD2-3	2.38	5.11	22.45	44.32
Mean LD2	2.38±0	5.66±0.64	22.54±0.30	38.57±5.07
LD3-1	2.49	4.22	28.00	56.15
LD3-2	2.44	4.61	27.84	61.58
LD3-3	2.55	4.75	29.83	57.25
Mean LD3	2.49±0.06	4.52±0.27	28.57±1.11	58.32±2.87
LD4-1	5.61	0.66	24.00	33.18
LD4-2	5.63	0.73	25.16	31.97
LD4-3	5.86	0.62	21.11	29.32
Mean LD4	5.70±0.14	0.67±0.06	23.42±2.09	31.49±1.97
LD5-1	6.18	0.40	21.03	31.63
LD5-2	6.18	0.50	15.41	23.03
LD5-3	6.11	0.41	17.29	24.86
Mean LD5	6.15±0.04	0.43±0.06	17.91±2.86	26.51±4.53
LD6-1	6.15	0.47	16.08	22.72
LD6-2	6.11	0.46	18.18	25.82
LD6-3	6.20	0.68	14.48	24.11
Mean LD6	6.15±0.05	0.54±0.12	16.25±1.86	24.21±1.55
LD7-1	2.40	4.96	53.78	44.22
LD7-2	2.55	4.87	48.66	41.85
LD7-3	2.52	5.33	48.78	39.19
Mean LD7	2.49±0.08	5.05±0.24	50.41±2.92	41.75±2.52
LD8-1	1.99	5.12	53.96	72.44
LD8-2	1.96	5.27	54.75	77.86
LD8-3	1.84	5.01	61.02	85.05
Mean LD8	1.93±0.08	5.13±0.13	56.58±3.87	78.45±6.33

On average, the total sulfur content (%TS) in leonardite was negatively correlated with the pH value i.e. the lower the pH value, the higher TS content in leonardite (Figure 1). The pH values of leonardite from Mae Moh and Lee mines (LD1, LD2, LD3, LD7 and LD8) were lower than 3 (1.84 to 2.55) with the TS ranging from 4.22 to 6.36% while the pH values of leonardite from Chiang Muan (LD7 and LD8) were higher than 5.5 with the TS range from 0.41 to 0.73% (Table 1 and Figure 1). Sulfur is considered essential in small amounts for the growth of most plants however excess amount in soil can be harmful to plant. Contaminated soil from beneath a sulfur block without liming, were acidic and contained high levels of soluble aluminum. $CaCO_3$ addition to sulfur-contaminated soils resulted in a neutral soil pH however $CaCO_3$ applications were not effective in promoting plant growth in soils with total sulphur levels above 4% [13]. Leonardite with high sulfur content has a high potential to produce more acidity by sulfur oxidation when incorporating into the soils. Soil acidity can reduce crop yield by directly affecting roots and increasing the availability of toxic elements. Most plants perform best at a soil with pH between >5.5 to 6.8 however, at present, the pH of most agricultural soil in Thailand is rather acidic due to excess input of agrochemicals [14]. For this reason, care should be taken when incorporating leonardite into the soils. Adjusting the pH of leonardite by lime or other materials which can raise its pH to the suitable range for crop production should be considered before soil application.

In spite of its very low pH, leonardite contained very high amount of humic acid. Humic substances (which includes humic acids) is formed through the process known as "humification". Humification is the natural transformation of organic matter into humic substances by microorganisms in the soil. The humification process that yields leonardite may take 70 million years. Leonardite possesses a high humic substance content as a result of being highly decomposed by microorganisms. Very low pH and high %TS might also due to highly decomposed process that accumulating organic acid and sulfur element. In the present study, it seemed that the higher humic acid content the lower pH level of leonardite (Figure 2). We suggested from our results that raising the pH level of leonardite by liming materials e.g. limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) prior to soil application is highly recommended. Natural soil typically has 1 to 5 percent humic and fulvic acids therefore limed leonardite application to increase humic acid level is of interest. Additionally, in contrast to compost, leonardite sourced humic acids do not compete with plants for nutrients, because leonardite-sourced humic acids are completely decomposed.

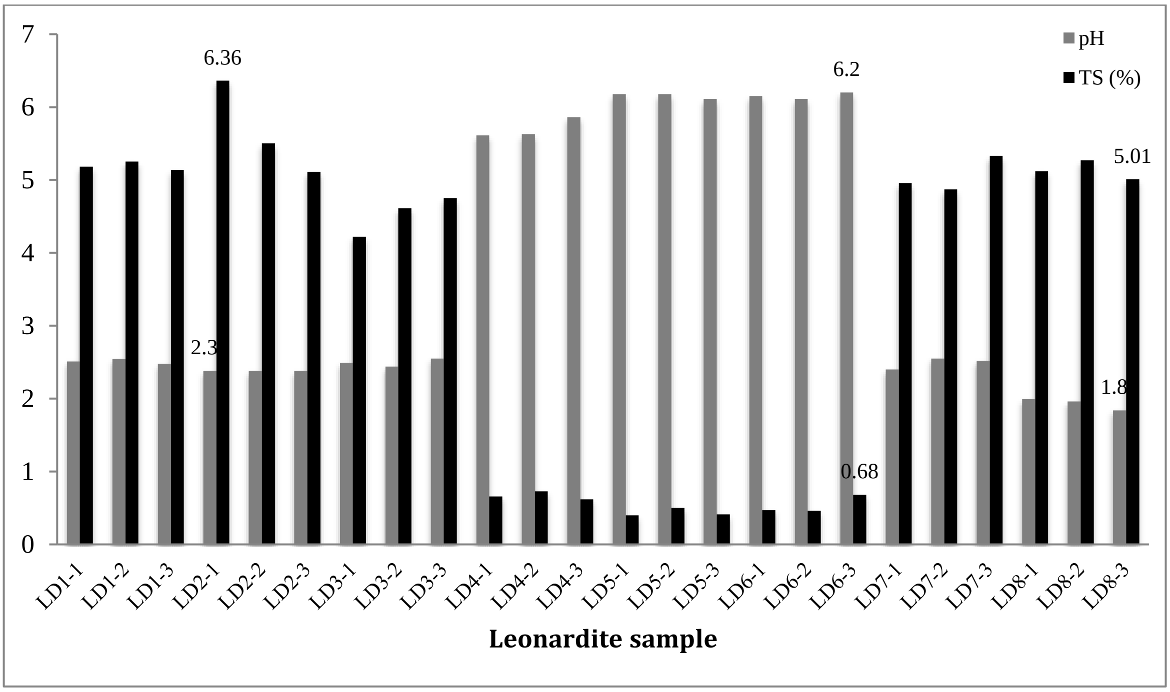

Figure 1 Comparison of pH and total sulfur (%TS) of leonardite samples.

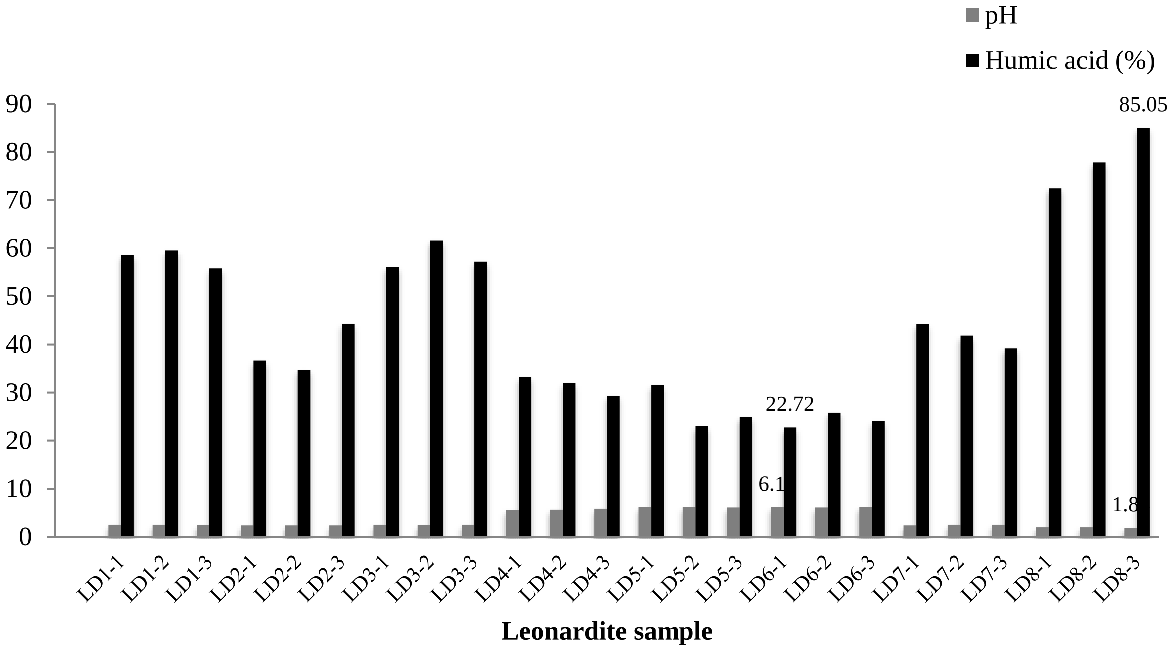

Figure 2 Comparison of pH and humic acid content in leonardite samples.

3.2 Nutrients level in leonardite samples

In addition to humic acid, leonardite can also be used to improve plant nutrients level in soils particularly micronutrients. Macronutrients (N, P and K) and micronutrients necessary for plant growth were found to be in large quantities particularly trace elements (Table 2). Macornutrients including total nitrogen (% N) and total potassium (%K) ranged from 0.25 to 0.60 %, and 0.84 to 2.24 %, respectively. From the results of other studies, total N varied widely from 0.73 to 1.79 % [10, 15, 16 & 17] and our results were somewhat in between these values. On average, high value of K was found in the samples collected from Lee mine (1.57 to 2.24% K). Alfredo et al., (2005) and Halil et al., 2011 [15 & 16] reported the analyzed concentration of K in leonardite to be 0.51 and 3.97 (%K), respectively. The major nutrients (N and K) contained in leonardite were in the range of higher than the standard values of organic fertilizer [7]. However, the total P values of all our leonardite samples were very low (28.6 to 211.2 mg kg^{-1}) and much lower than the organic fertilizer standard values (>0.5%). The results were in accordance with all the previous reports of P concentration in leonardite [10, 15, 16 & 17]. Percentage of Ca and Mg of our samples ranged from 0.55 to 3.36 % and 0.30 to 0.78%, respectively. On average Ca and Mg contents in compost range from 1.2 to 4.5% and 0.3 to 0.57%, respectively, depending on type of raw material use for composting [12]. The analyzed values of trace elements were as follows; Fe, 1.62 to 5.33%, Zn 19 to 149 mg kg^{-1} and Mn 50 to 202 mg kg^{-1}, which are consistent with those by Ali et al., (2007), Alfredo et al., (2005) and John et al., (1998) [10, 15 & 17]. Our results suggested that the P content of leonardite should be raised by applying high P materials such as rock phosphate before being developed as soil amendment and/or organic fertilizer. In addition, the pH values of the soil mixed with leonardite should be measured prior to crop cultivation since the Fe content in leonardite was quite high and might be toxic to the plant at low pH due to high solubility of all trace elements.

3.3 Element analysis of minerals by X-ray diffraction (XRD)

Only five samples of leonardite were selected from chemical analysis of leonardite (3.1 and 3.2). The samples include LD 2-3 (Mae Moh 2), LD3-2 (Mae Moh 3), LD4-2 (Chiang Muan2), LD8-1 (Lee 2) and LD8-3 (Lee 2). The analysis of the composition of mineral X-ray diffraction (XRD) showed that all the samples mainly consist of silica (Si) group of Quartz, Feldspar group of albite and brushite and also the ingredients clay minerals of kaolinite illite niter and montmrillonite (Table 3, Figure 3). Our results were in consistent with those of Chammui (2014) [18] who found that the XRD pattern of leonardite indicated the clay mineral characteristic (e.g. montmorillonite), and other minerals i.e. gypsum, pyrite and quartz.

Table 2 Nutrients content of leonardite samples

Leonardite sample	Total N (%)	Total P (mg kg^{-1})	Total K (%)	Ca (%)	Mg (%)	Fe (%)	Zn (mg kg^{-1})	Mn (mg kg^{-1})
LD1-1	0.48	149.6	1.33	1.88	0.57	3.25	75	110
LD1-2	0.55	167.2	1.39	2.00	0.55	3.11	77	109
LD1-3	0.60	149.6	1.39	2.22	0.54	3.22	54	102
Mean LD1	0.54±0.06	155±10.2	1.37±0.03	2.03±0.17	0.55±0.02	3.19±0.07	68.7±12.7	107±4.36
LD2-1	0.51	145.2	1.24	3.03	0.39	5.33	58	86
LD2-2	0.51	167.2	1.16	3.05	0.43	5.24	56	86
LD2-3	0.49	162.8	1.18	3.36	0.42	5.10	67	85
Mean LD2	0.50±0.01	158±11.6	1.19±0.04	3.15±0.19	0.41±0.02	5.22±0.12	60.3±5.86	85.7±0.58
LD3-1	0.54	202.4	1.19	1.98	0.50	3.21	69	112
LD3-2	0.55	211.2	1.31	1.81	0.52	3.24	61	123
LD3-3	0.57	211.2	1.25	2.10	0.51	3.35	63	126
Mean LD3	0.55±0.02	208±5.08	1.25±0.06	1.96±0.15	0.51±0.01	3.27±0.07	64.3±4.16	102±7.37
LD4-1	0.34	41.8	0.90	0.71	0.70	1.73	80	50
LD4-2	0.36	31.2	0.84	0.71	0.70	1.63	63	60
LD4-3	0.31	28.6	0.92	0.64	0.72	1.69	67	52
Mean LD4	0.34±0.03	34±6.99	0.89±0.04	0.69±0.04	0.71±0.01	1.68±0.05	70.0±8.89	54±5.29
LD5-1	0.33	38.3	1.13	0.66	0.72	1.78	63	57
LD5-2	0.27	37.4	1.20	0.56	0.74	1.83	81	62
LD5-3	0.28	38.7	1.14	0.57	0.73	1.79	80	55
Mean LD5	0.29±0.03	38±0.67	1.16±0.04	0.60±0.06	0.73±0.01	1.80±0.03	74.7±10.1	58±3.61
LD6-1	0.25	32.1	0.93	0.55	0.74	1.70	49	52
LD6-2	0.28	29.0	0.96	0.55	0.73	1.62	64	56
LD6-3	0.26	30.4	0.99	0.56	0.72	1.64	78	58
Mean LD6	0.26±0.02	31±1.55	0.96±0.03	0.55±0.01	0.73±0.01	1.65±0.04	63.7±14.5	55.3±3.06
LD7-1	0.45	172.8	2.16	0.72	0.63	2.18	139	197
LD7-2	0.42	149.6	2.24	0.70	0.78	2.02	147	202
LD7-3	0.43	136.1	2.13	1.92	0.40	1.89	149	212
Mean LD7	0.43±0.02	153±18.6	2.18±0.06	1.11±0.70	0.60±0.19	2.03±0.15	145±5.29	203±7.64
LD8-1	0.45	97.6	1.61	1.82	0.39	1.75	30	83
LD8-2	0.48	66.8	1.81	1.54	0.47	2.67	25	86
LD8-3	0.57	123.6	1.57	1.73	0.30	2.31	19	88
Mean LD8	0.50±0.06	96±28.4	1.66±0.13	1.70±0.14	0.39±0.09	2.24±0.46	24.7±5.51	85.7±2.52

Table 3 Minerals composition of leonardite examined by XRD analysis

Sample code	Location	Mineral composition [1]
LD 2-3	Mae Moh 2	Quartz, albite, brushite, kaolinite and illite
LD3-2	Mae Moh 3	Quartz, brushite, kaolinite and illite
LD4-2	Chiang Muan 2	Quartz, brushite, kaolinite, illite and montmorillonite
LD8-1	Lee2	Quartz, brushite and niter
LD8-3	Lee2	Quartz, brushite, illite and niter

[1]Quartz=SiO_2, albite=$Na(AlSi_3O_8)$, brushite=$CaPO_3(OH)\bullet 2H_2O$, kaolinite=$Al_4(OH)_8(Si_4O_{10})$, illite=$K(AlFe)2AlSi_3O_{10}(OH)_2\bullet H_2O)$, montmorillonite = $3MgO \bullet 4SiO_2\bullet H_2O$ and niter = KNO_3

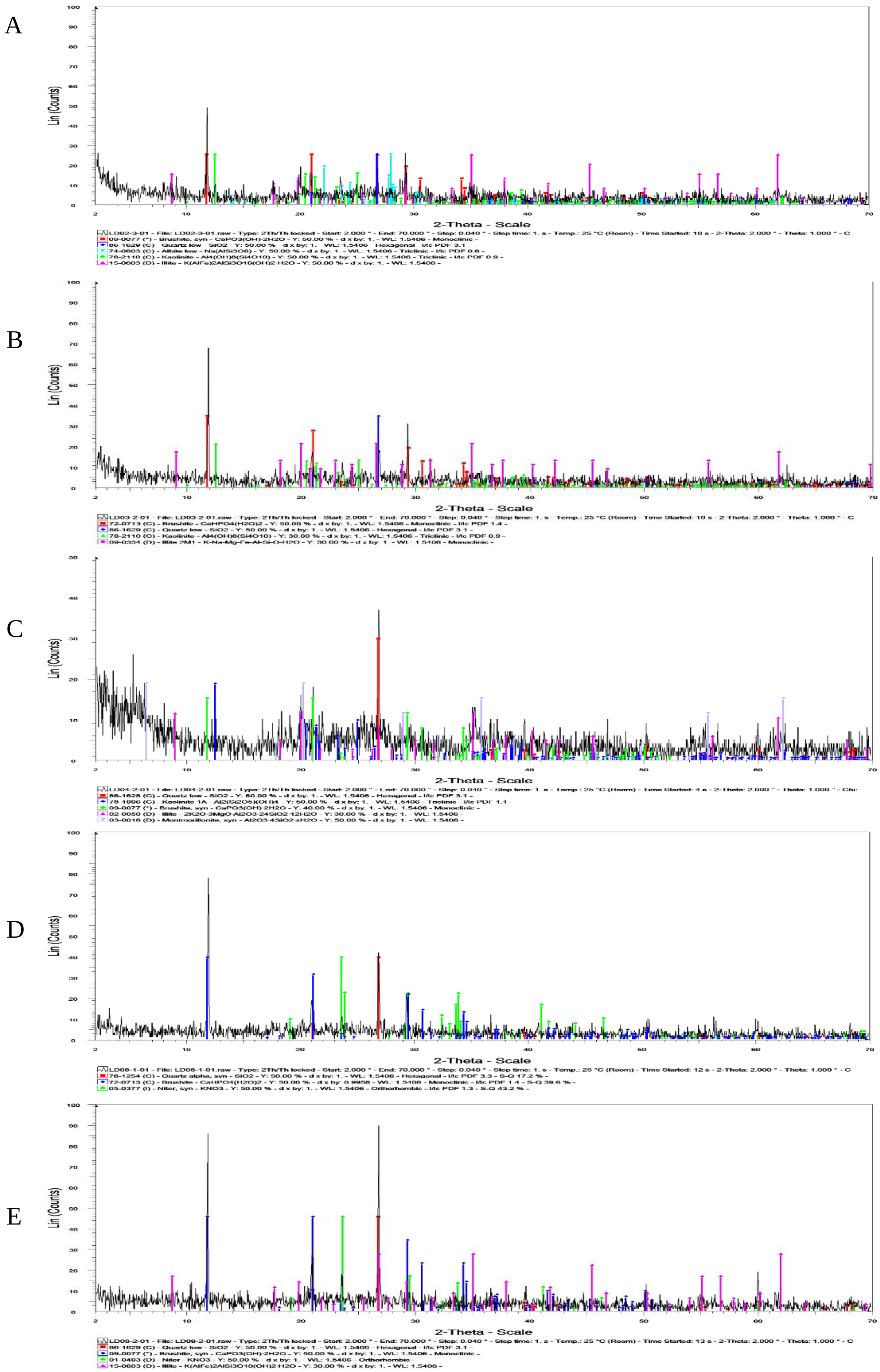

Figure 3 X-Ray diffraction patterns of leonardite samples**:** LD 2**-**3 **(**Mae Moh 2**)** **(**A**)**, LD3**-**2 **(**Mae Moh 3**)(**B**)**, LD4**-**2 **(**Chiang Muan2**)** **(**C**)**, LD8**-**1 **(**Lee 1**)** **(**D**)** and LD8**-**3 **(**Lee 2 **)** **(**E**).**

Table 4 Elemental analysis of leonardite samples by X-ray fluorescence spectrometry

Compound (wt%)	Leonardite samples				
	LD2-3	LD3-2	LD4-2	LD8-1	LD8-3
Al_2O_3	12.84	8.79	14.61	3.72	4.94
Fe_2O_3	4.74	9.26	2.86	4.80	6.56
K_2O	2.92	3.64	2.26	1.23	2.03
MgO	1.11	0.73	1.68	0.20	0.31
MnO	<0.01	0.02	<0.01	0.01	0.01
Na_2O	1.23	0.40	0.22	1.72	0.21
P_2O_5	1.18	2.87	1.11	0.59	0.65
SiO_2	35.24	35.15	48.30	16.42	23.41
TiO_2	0.51	0.42	0.59	0.34	0.38
CaO	3.72	5.83	2.31	4.17	4.35
PbO	N.D.	0.72	N.D.	N.D.	N.D.
Rb_2O	N.D.	N.D.	N.D.	N.D.	N.D.
BaO	<0.01	<0.01	<0.01	N.D.	N.D.
SO_3+Loss on Ignition (LOI)	36.56	32.56	26.41	66.79	57.10
Total	100.04	100.39	100.35	99.99	99.95

N.D. = Not Detectable

3.4 The analysis of the elemental content by X-ray fluorescence spectrometry (XRF)

The analysis of the elemental content by X-ray fluorescence spectro- metry (XRF) indicated that the leonardite sample consist of various elements: Si, Al, K, Fe, Mg, Mn, P, Na, Ca and Ti elemental composition. The element Si is the most abundant element (26.41 to 66.79%) (Table 4). This was consistent with XRD analysis (Table 3, Figure 3) that showed the highest content of Quartz (SiO_2) in leonardite. The high Si content in leonardite seemed to be beneficial to use as soil fertility improvement. Long period of intensive crop cultivation depletes the available soil silicon (Si). In the tropical areas, depletion of available Si in the soil could be one of the possible limiting factors amongst others contributing to declining crop yield [19]. Therefore, tropical soils would be benefit from leonardite application. On the average, the elements Al and Fe seemed to be the highest after Si. The values ranged from 3.72 to 14.61 and 2.86 to 9.26 %wt., respectively. With high total sulfur, Al and Fe, as a result when the dissolution of leonardite takes place, the pH of the material was extremely acidic.

3.5 Structure Characterization of leonardite by SEM

The surface appearance, size and shape of leonardite powder was shown in Figure 4. The images showed that the surface leonardite was a thin layer, flat sheet of splice overlap. The leonardite sample, LD4-2 was assumed to be contaminated by soil. Thus, as shown in the figure, the overlay of the flat sheet seemed to be tighter than leonardite from other sources. However, the overall appearances of leonardite from the various sources are not very different. The layer structure of leonardite with its high humic acid and nutrients content, could provide as carrier material for biofertilizer production. However, the role of leonardite in maintaining microbial population has not been studied. Therefore, it would be of interest to test the effects of this material on microbial growth.

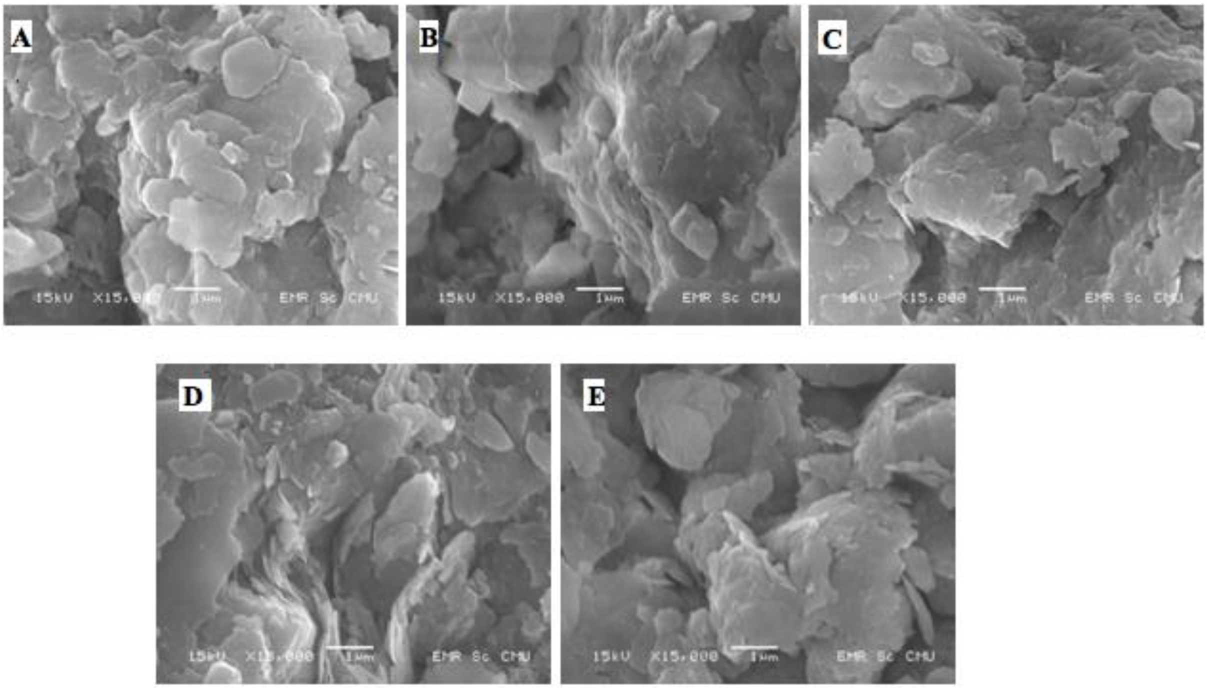

Figure 4 SEM images of leonardite samples: LD 2-3: Mae Moh 2 (A), LD3-2: Mae Moh 3 (B), LD4-2: Chiang Muan2 (C), LD8-1: Lee 2 (D) and LD8-3: Lee 2 (E).

4. Conclusion

The properties of leonardite varied from one deposit to another. Despite the low pH (pH <3) and low P levels of most leonardite samples, they contained quite high humic acid, major plant nutrients (except for P) and high trace elements. Chemical properties indicated high potential of leonardite to use as a soil conditioner for soil fertility and crop yield improvement. However, some properties such as pH value and P content should be improved before soil application. Chemical analysis by XRD and XRF indicated that all the samples mainly consist of Silica (Si) thus a good source of Si for plant growth. The pH values of the soil applied with leonardite should be measured prior to crop cultivation since the Al and Fe content in leonardite was quite high and might be toxic to the plant at low pH due to their high solubility. The layer structure of leonardite powder with their high organic matter and nutrients content might be suitable for microbial growth.

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