International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Role of Aggregates and Clay Minerals in Carbon Mitigation of Sodic Soil

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ABSTRACT

The aim of this study was to analyze soil aggregate carbon storage and clay mineralogy of sodic soils located in the Panipat district of Haryana, India (Panipat, Samalkha and Israna blocks; 29.39°N, 76.97°E; average elevation 219 m / 718 ft). The soils were strongly alkaline, with pH values ranging from 8.86 to 9.11. The climate of the region is semi-arid and monsoonic. Soil analysis showed that microaggregates (250–53 µm and <53 µm) constituted the largest fraction of soil aggregates and played a dominant role in protecting soil organic carbon (SOC). The total carbon content was higher in microaggregates (250–53 µm) compared to the silt- and clay-associated fractions (<53 µm). Soil aggregate carbon biomass exhibited a significant relationship with SOC across different soil depths. Clay mineralogical analysis revealed that montmorillonite, chlorite, illite, kaolinite, and vermiculite were the dominant clay minerals present in the soils. The findings suggest that conservation of native wild vegetation on salt-affected soils can enhance carbon sequestration by improving soil structure and increasing SOC storage within aggregate fractions. In sodic soils, aggregates and clay minerals are the twin pillars of carbon stabilization. While sodicity disrupts both, reclamation practices that restore aggregation and clay reactivity can transform degraded soils into effective carbon sinks. Harnessing this mechanism not only improves soil fertility and productivity but also contributes significantly to climate change mitigation strategies.

Keywords: Soil aggregates, Soil aggregate carbon, wild grassland systems, clay minerals

Introduction

Soil salinity and sodicity represent major forms of land degradation in arid and semi-arid regions worldwide. Sodic soils are characterized by high exchangeable sodium percentage (ESP), elevated pH, and poor physical structure. These conditions degrade soil aggregation, reduce infiltration, and make soils vulnerable to erosion and organic carbon loss. Enhancing carbon storage in such soils is crucial for improving soil health, crop productivity, and mitigating atmospheric CO_2. Two key factors that influence carbon stabilization are soil aggregates and clay minerals. In India, approximately 9.38 million hectares of land are affected by salinity, of which 3.88 million hectares comprise alkali/sodic soils (IAB, 2000). Soil organic matter (SOM) is a vital renewable resource that must be restored in degraded landscapes, as it regulates the physical, chemical, and biological properties of soils (Sanchez, 1995). The retention and accumulation of soil carbon are particularly critical for maintaining soil fertility and sustaining the productivity of salt-affected soils.

Despite its importance, soil carbon dynamics in sodic soils remain poorly studied, with only limited investigations available (Singh, 1995; Singh et al., 1997; Bhojvaid et al., 1996; Kaur et al., 2002). This knowledge gap highlights the need for detailed research on carbon storage, stabilization mechanisms, and management practices in sodic soils to support ecological restoration and sustainable land use.

Soil aggregates play a fundamental role in maintaining soil health by influencing several key processes, including water movement and storage, soil aeration, physical protection of soil organic matter (SOM), prevention of erosion, root penetration, and microbial activity (Tisdall and Oades, 1982; Tate, 1995). Soil aggregates act as physical barriers that occlude particulate organic matter (POM) inside micro- and macro-aggregates, shielding it from microbial attack. The soil organic carbon (SOC) associated with aggregates forms an important and relatively stable carbon reservoir, as it is physically protected from mineralization and enzymatic degradation (Trujillo et al., 1997).

To study these dynamics, physical fractionation techniques have been widely employed to separate SOM pools into distinct size classes: primary particles (sand, silt, and clay), microaggregates (53–250 µm), and macroaggregates (>250 µm) (Tisdall and Oades, 1982). These aggregate fractions differ in their ability to stabilize and protect carbon, thereby playing a crucial role in soil carbon sequestration and overall soil quality. Macroaggregates (>250 µm) often enclose fresh plant residues and particulate carbon while Microaggregates (<250 µm), formed inside macroaggregates, provide long-term stabilization of carbon. High exchangeable sodium percentage (ESP) of sodic soils disperses clay particles, weakens binding agents, and disrupts aggregate stability, exposing organic carbon to decomposition.

Clay minerals exert a profound influence on the physical and chemical properties of soils, as well as on the stabilization and chemical composition of soil organic matter (SOM). Clay mineralogy plays a key role in regulating the quantity of organic carbon stored in soils, its turnover rates, and the exchange of carbon between soils and the atmosphere during long-term soil development (Torn et al., 1997; Laird, 2001). Despite this importance, research on the clay mineralogy of salt-affected soils remains limited. Greater attention is required to understand how interparticle interactions among soil minerals influence soil carbon stability, particularly in degraded and sodic landscapes.

Keeping in view the importance of salt-adapted native vegetation in the rehabilitation of salt-affected soils, this study aimed to analyze soil aggregate–associated carbon storage and to examine the role of clay mineralogy in regulating soil carbon stability.

MATERIAL AND METHODS

Study area

The study was conducted in a wild vegetation system dominated by Desmostachya bipinnata (L.) Stapf and Sporobolus marginatus Hochst., growing on sodic soils in Panipat district (Samalkha and Israna blocks; 29.39°N, 76.97°E; average elevation 219 m / 718 ft) located in the central-eastern part of Haryana, India. The climate of the study area is semi-arid, characterized by hot summers, cool winters, and a monsoonal rainy season extending from June to September. During the study period (March 2023–February 2024), the total rainfall recorded was 362 mm. The mean maximum temperature ranged from 29.21°C to 30.66°C, while the mean minimum temperature varied between 18.37°C and 19.98°C.

The soils of the study area are highly alkaline, with pH values ranging from 9.8 to 10.2, and are distributed across three blocks of Panipat district—Israna, Panipat, and Samalkha. In the Israna block, soil samples were collected from Mandi, Puthar, Bandh, Shahpur, and Nain adjoining areas. In the Samalkha block, samples were obtained from Bapoli and Ujjah, while in the Panipat block; sampling sites included Barana, Faridpur, Barsat, Gad Palehari, and Babail in the northeastern portion, as well as Bhalsi, Kalkhan, and Luhari in the western part of the district. All these sites are characterized by a sparse cover of salt-adapted wild vegetation. A calcic hardpan, occurring at a depth of 80–120 cm, was commonly observed in these soils, leading to impeded drainage conditions. During study time, the soil pH varied from 8.86 to 10.03 at 0-5cm and 15-30cm soil depths, respectively. Soil organic carbon of the grassland sites was low and ranged from 0.46 to 0.12% across soil depths (Table 1).

Analysis of soil aggregate composition

Replicated field-moist soil samples were collected from three depths (0–5 cm, 5–15 cm, and 15–30 cm). Sub-samples were gently crumbled by hand and passed through an 8 mm sieve to remove roots, after which they were air-dried for aggregate analysis. Soil aggregate size distribution was determined using the wet sieving method described by Elliott (1986). The aggregates were separated into four size classes: >2 mm, 2 mm–250 µm, 250 µm–53 µm, and <53 µm. Each aggregate fraction was oven-dried at 80 °C to obtain weights on an oven-dry basis.

Analysis of soil aggregate organic carbon

Sub-samples of air-dried soil and separated soil aggregates were analyzed for organic carbon using the dichromate oxidation method (Kalembasa and Jenkinson, 1973). Soil organic carbon (SOC) stock at each depth was calculated based on bulk density, soil depth, and organic carbon concentration of the corresponding soil layer.

Soil clay mineralogy

The <2 µm clay fraction, separated from the soil, was used to examine the clay mineralogical composition by X-ray diffraction (XRD). Oriented clay samples were prepared, and two treatments were applied: glycolation and glycolation followed by heating at 550 °C for 4 hours. XRD analysis was performed using an XPERT-PRO diffractometer with Cu as the anode material, employing CuKα radiation at 45 kV and 40 mA. Samples were scanned in continuous mode at a step size of 0.017°, over a 2θ range of 4–40° for untreated samples and 4–60° for glycolated samples. Relative mineral contents in the clay fraction were semi-quantitatively estimated based on XRD peak intensities, assuming proportionality between peak intensity and mineral content, and normalized to 100%.

Statistical analysis

Data on soil carbon, soil aggregates, and microbial biomass carbon were analyzed using one-way analysis of variance (ANOVA). Least significant difference (LSD) values at the 5% level of significance ($p \leq 0.05$) were calculated following the procedure of Gomez and Gomez (1984). In addition, regression analysis was performed to examine the relationship between soil aggregate-associated carbon and total soil carbon.

Results and Discussion

The Desmostachya bipinnata-dominated wild vegetation system, occurring on soils with a surface pH of 8.6, was comprised of Cynodon dactylon (L.) Pers. (23.4 plants m^{-2}), Cyperus rotundus L. (3.6 plants m^{-2}), Erigeron linifolius Willd. (5.6 plants m^{-2}), Leptochloa panacea (6.6 plants m^{-2}), and Rumex dentatus L. (1.0 plants m^{-2}). In contrast, the Sporobolus marginatus Hochst.-dominated system, occurring on soils with a pH of 9.11, consisted of Sporobolus marginatus (818 plants m^{-2}), Cynodon dactylon (L.) Pers. (30.4 plants m^{-2}), Dichanthium annulatum (Forssk.) Stapf (11.0 plants m^{-2}), and Digitaria sanguinalis (12.6 plants m^{-2}). The number of forbs (non-leguminous species) was higher at the D. bipinnata site (8–9 species) compared with the S. marginatus site (4–5 species).

Soil aggregate composition and carbon storage

At all study sites, only a small proportion of macroaggregates (2 mm–250 µm) was recovered from soils up to 0–30 cm depth (Table 2). The share of small macroaggregates was higher in the Desmostachya bipinnata-dominated grassland (4.42–5.45%) compared with the Sporobolus marginatus-dominated system (3.10–3.79%). Microaggregates (250 µm–53 µm) accounted for 28.12–38.34% of soil aggregates in S. marginatus sites and 56.41–61.56% in D. bipinnata sites. Clay- and silt-associated aggregates (<53 µm) formed the largest fraction in S. marginatus soils (58.00–68.09%), whereas their proportion was lower in D. bipinnata soils (34.02–38.14%).

Carbon concentration was consistently higher in macroaggregates than in microaggregates (Table 3). In macroaggregates, C concentration ranged from 0.19–0.41% (S. marginatus) and 0.28–0.58% (D. bipinnata). Microaggregates contained 0.13–0.25% C (S. marginatus) and 0.16–0.33% (D. bipinnata). The silt- and clay-sized fraction showed lower concentrations, ranging from 0.09–0.21% (S. marginatus) and 0.09–0.20% (D. bipinnata). These differences in organic carbon storage across aggregate size classes likely reflect differences in organic matter inputs, decomposition rates of litter and fine roots, and clay–silt content. Notably, the clay and silt content of soils increased with depth. Overall, soil organic carbon (SOC) was significantly correlated with aggregate-associated carbon.

Across soil depths, organic carbon concentration decreased from macroaggregates to microaggregates. Macroaggregates are primarily stabilized by recent inputs of residues and carbohydrate-rich root or plant debris occluded within aggregates (Golchin et al., 1994). In contrast, silt and clay fractions play a crucial role in long-term stabilization of SOC (Six et al., 2002). In this study, silt + clay fractions stored 1.202–4.646 g C kg^{-1} aggregate fraction, compared with 0.443–1.533 g C kg^{-1} in microaggregates and only 0.062–0.537 g C kg^{-1} in macroaggregates.

Macroaggregates are generally sensitive to disturbance, whereas microaggregates are more stable and resistant. SOC within microaggregates is thought to be protected from decomposition, making it important for long-term carbon sequestration. In contrast, loss of carbon from macroaggregates is more rapid due to weaker biophysical and chemical protection mechanisms (Jastrow and Miller, 1998).

Clay Mineralogy

X-ray powder diffraction (XRD) is the most widely used technique for characterizing crystalline structures and determining the mineralogy of fine-grained sediments, particularly clays. It provides both qualitative and semi-quantitative information on soil mineral composition. The angles of diffraction, influenced by different sample treatments, are distinctive for particular minerals and allow their identification. The intensities of diffraction maxima are proportional to the number of corresponding diffraction planes in a sample and thus form the basis for estimating relative mineral concentrations.

The XRD patterns of oriented, glycolated, and glycolated-heated samples of sodic soils from Panipat district are shown in Figures 1 and 2. The clay fraction was dominated by illite, identified by the characteristic 3.34 Å peak along with its higher-order reflections at 10.01 Å and 4.981 Å. The presence of chamosite was indicated by sharp peaks at 7.077 Å in glycolated samples, which disappeared after heating at 550 °C, confirming its identity. Peaks at 3.030 Å, 3.201 Å, and 3.53 Å in oriented samples confirmed the presence of calcite, muscovite, and chlorite, respectively. In glycolated and glycolated-heated samples, the dominance of illite and mica was further supported by peaks at 3.34 Å and 10.01 Å.

Clay minerals provide large surface areas and reactive sites for adsorption of organic compounds. Illite is considered a key precursor mineral for the formation of smectite in salt-affected soils. In this study, illite and montmorillonite (a 2:1 smectite group mineral) were predominant in the clay fraction whose expandable layers allow intercalation of organic molecules, enhancing protection of organic carbon. Gonzalez and Laird (2003) demonstrated that newly formed humic substances tend to accumulate preferentially on smectite surfaces, suggesting an important role of these minerals in stabilizing soil organic matter. The predominance of illite and montmorillonite in the studied soils may therefore play a critical role in soil carbon stability, as mineral–organic associations are a major determinant of carbon storage. The stabilization of organic matter within soils depends on the chemical properties of the mineral fraction and the surface area available for adsorption (Baldock and Skjemstad, 2000). In arid and semi-arid regions, smectite, chlorite, illite, kaolinite, and vermiculite typically dominate the clay mineral assemblage (Gonzalez and Laird, 2003). The transformation of plant residues into stable clay–humus complexes is a key process regulating soil quality and determining whether soils act as net carbon sinks or sources (Gonzalez and Laird, 2003).

Conclusion

In sodic soils, microaggregates (250–53 µm) and fine fractions (<53 µm) represent the dominant aggregate classes and play a critical role in protecting soil organic carbon (SOC). The maintenance of native wild vegetation on salt-affected soils enhances carbon sequestration by improving aggregate stability and increasing SOC storage within finer fractions. The predominance of illite and montmorillonite in these soils further contributes to carbon stabilization through organo–mineral associations, which limit microbial decomposition by providing physical enclosure and reactive adsorption sites. Thus, the combined effects of soil aggregation and clay mineralogy act as key mechanisms for SOC stabilization in sodic ecosystems. Reclamation measures, when integrated with conservation of wild vegetation, not only restore soil structure and fertility but also transform degraded lands into effective carbon sinks—contributing to biodiversity conservation and climate change mitigation strategies.

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Table 1

Some physical and chemical soil characteristics at different soil depths in *Sporobolus marginatus* and *Desmostachya bipinnata* dominated wild vegetation systems on sodic soils at Panipat district

Study sites/ soil depth	Soil pH	Organic C (%)	Bulk density (g cm^{-3})
Sporobolus marginatus **dominated wild vegetation system**			
0 – 5 cm	9.11±0.08	0.32±0.02	1.53±0.02
5-15cm	10.00±0.03	0.19±0.01	1.59±0.02
15-30cm	10.03±0.04	0.12±0.016	1.64±0.01
LSD ($p \leq 0.05$)	0.168	0.062	0.064
Desmostachya bipinnata **dominated wild vegetation system**			
0 – 5 cm	8.86±0.11	0.46±0.02	1.50±0.02
5-15cm	9.72±0.03	0.23±0.02	1.57±0.025
15-30cm	10.01±0.05	0.17±0.01	1.61±0.02
LSD ($p \leq 0.05$)	0.227	0.062	0.078

Table 2

Percent soil weight distribution in aggregate size classes in wild vegetation system across soil depths at Panipat district (± standard error).

Soil depth (cm)	Percent soil weight in soil aggregates		
	2 mm – 250 µm	250µm – 53 µm	<53µm
Sporobolus marginatus dominated wild vegetation system			
0 – 5	3.79±0.77	28.12±1.85	68.09±0.42
5 – 15	3.10±0.43	32.78±1.98	64.12±1.23
15 – 30	3.66±0.58	38.34±1.60	58.00±2.85
LSD (p<0.05)	1.36	5.87	3.79
CV (%)	23.76	9.91	3.40
Desmostachya bipinnata dominated wild vegetation system			
0 – 5	5.45±0.32	56.41±1.26	38.14±1.60
5 – 15	4.79±0.77	59.18±2.84	36.03±0.81
15 – 30	4.42±0.74	61.56±1.09	34.02±1.05
LSD (p<0.05)	1.36	4.42	4.30
CV (%)	15.89	4.25	6.83

Table 3

Organic carbon distribution in aggregate size classes in soils of grassland system at various soil depths at Panipat district (± standard error).

Soil depth (cm)	Organic carbon (%)			
	Soil	2 mm – 250 µm	250µm – 53 µm	<53µm
Sporobolus marginatus dominated wild vegetation system				
0 – 5	0.32±0.01	0.41±0.01	0.25±0.02	0.21±0.01
5 – 15	0.19±0.01	0.31±0.02	0.18±0.01	0.16±0.01
15 – 30	0.12±0.01	0.19±0.01	0.13±0.01	0.09±0.01
LSD(p<0.05)	0.062	0.067	0.059	0.034
CV (%)	18.08	12.63	17.88	13.20
Desmostachya bipinnata dominated wild vegetation system				
0 – 5	0.46±0.01	0.58±0.03	0.33±0.01	0.20±0.01
5 – 15	0.23±0.01	0.33±0.02	0.22±0.01	0.16±0.01

15 – 30	0.17±0.01	0.28±0.01	0.16±0.02	0.09±0.01
LSD(p<0.05)	0.062	0.059	0.045	0.034
CV (%)	13.36	9.15	10.52	11.07

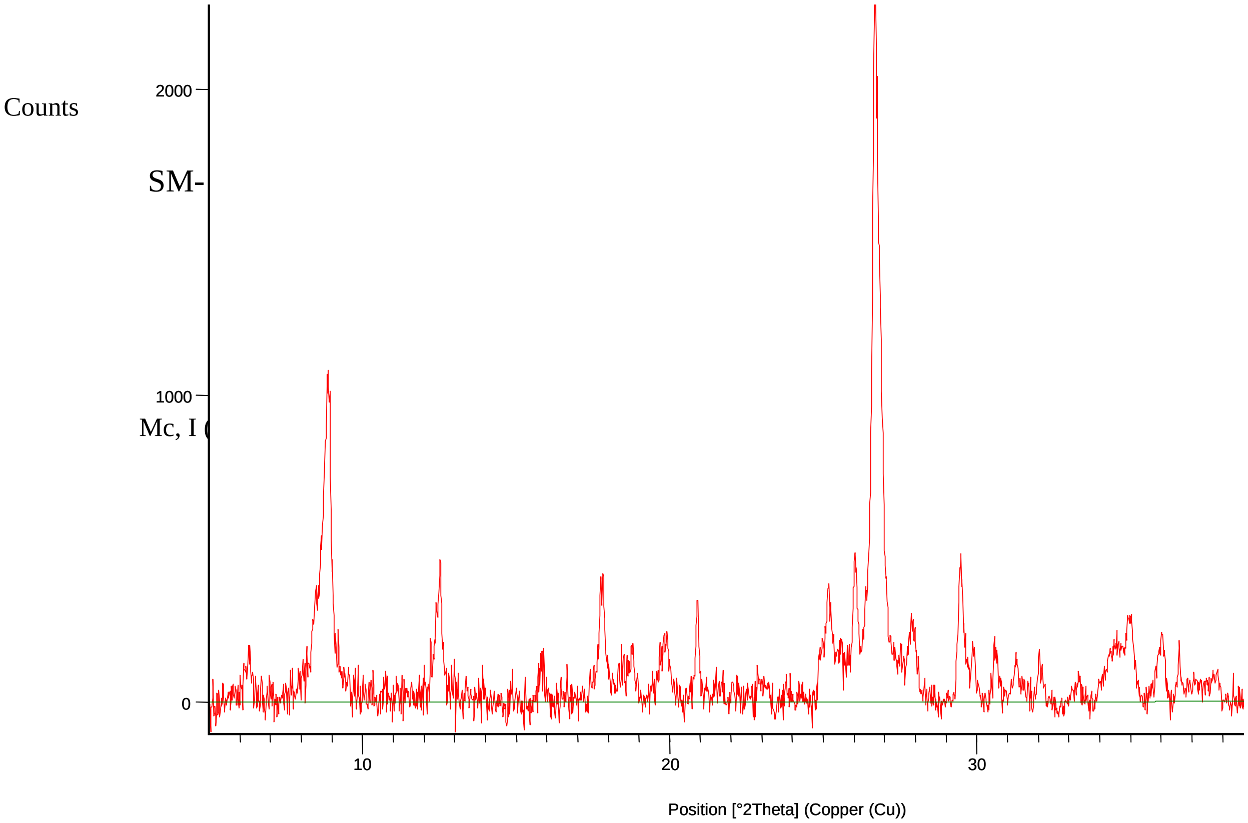

Figure 1. X-ray diffraction pattern of untreated clay from highly sodic soil at Panipat district (I = Illite; Mc = Mica; Ch = Chlorite; M = Montmorillonite; Ca = Calcite; Cm = Chasmosite).

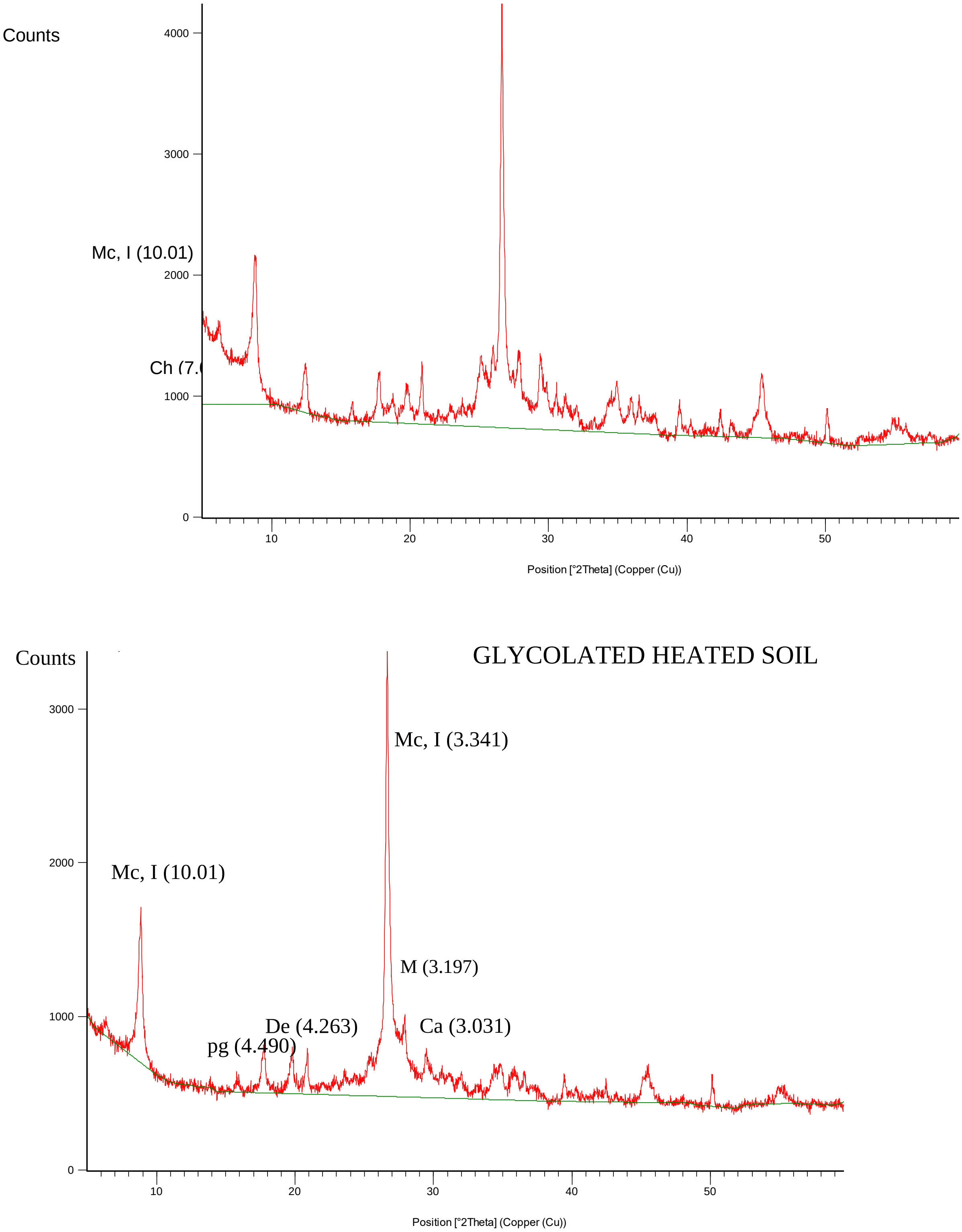

Figure 2. X-ray diffraction pattern of clay fraction from highly sodic soil at Panipat district. (a) Glycolated (I = Illite; Mc = Mica; Ch = Chlorite; De = Dickite; Ca = Calcite).
(b) Glycolated Heated Clay (I = Illite; M = Montmorillonite; Mc = Mica; Ca = Calcite; De = Dickite).