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Study on plasticity and compressibility behaviour of jute and coir reinforced soft soil

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Abstract

Expansive soft soils exhibit high plasticity and compressibility, resulting in excessive settlement and poor engineering performance. This study evaluates the effectiveness of coir and jute fibers as sustainable reinforcement materials for improving the plasticity and compressibility behavior of soft soil through laboratory and microstructural characterization. Fibers measuring 1 cm were randomly incorporated at 0.5-2.5% by dry weight of soil. Atterberg limits, compaction, unconfined compressive strength (UCS), one-dimensional consolidation, X-ray diffraction (XRD), and scanning electron microscopy (SEM) were employed. Coir reduced the liquid limit from 82.0% to 74.31%, whereas jute reduced it to 76.98%. The plasticity index decreased by 26.73% for coir and 22.65% for jute, while the shrinkage limit increased from 11.28% to 15.18% and 16.52%, respectively. Coir increased the maximum dry density from 13.71 to 15.62 kN/m³, whereas jute achieved 14.88 kN/m³. The highest UCS of 97.34 kPa was obtained with 2% coir, representing a 78.62% improvement over unreinforced soil, while jute reached 81.82 kPa at 2.5% fiber content. Consolidation tests showed lower compression index and compressibility together with higher consolidation coefficients, indicating reduced settlement potential. XRD confirmed that reinforcement retained the original soil mineralogy, while SEM revealed fiber bridging, particle interlocking and pore refinement as the dominant strengthening mechanisms. Overall, 2% Coir provided the best engineering performance; however, jute showed greater improvement in shrinkage resistance, suggesting the potential of natural fibers for sustainable soft-soil stabilization. These findings demonstrate that natural fibers provide an environmentally responsible alternative for enhancing expansive soft soils without inducing mineralogical changes sustainably.

Keywords: soft soil; fiber; compressive strength; consolidation; volume change.

1. Introduction

Clay soils cause large settlements to structures [1]. They are characterized by high in-situ moisture content and high compressibility. The clay soil can pose severe threat to structures such as embankment, highways and retaining structures due to low bearing capacity and high differential settlement. Additives like lime, silica fume and polypropylene and use of coir geotextile. Layered geotextile mat at various depths were able to reduce the swelling pressure to 52.19% and 81.89% for one and two layer of coir geotextile respectively [2]. It is necessary to determine the engineering characteristics of the soft clay, including its including shear

strength, permeability and stiffness. These characteristics could be enhanced by chemical stabilisation and reinforcement inclusions [3]. The design properties of soil can be greatly improved by adding chemical additives like lime, cement, and fly ash [4]. Recently, reinforcing fibers have been introduced to soft clay to improve the soil. Fibers enhance the engineering qualities of soil, including its bearing capacity, tensile strength, ductility, and shear and compressive strengths. Due to their superior engineering capabilities over natural or vegetable fibers, traditional synthetic fibers are used in soil reinforcement. However, financial analysis favours the use of natural fibers because they require less energy and are far relatively cheap to produce. Natural fibers are also renewable resources because they are produced by taking in carbon dioxide and releasing oxygen back to the environment atmosphere [5]. Reinforcing soil with fibers can improve its stability and reduces deformations and failure [6]. Natural and synthetic fibers have been used in recent research and numerous field applications. Natural fibers, which are abundantly present, such as coir, jute, hemp and sisal fibers have been adopted in recent times. The fibers differ in their basic mechanical and biochemical properties. The percentage of lignin, cellulose and hemicellulose compositions differ depending on the type of fiber. These compositions vary for coir, jute and other fibers and basically influences, tensile strength, water absorption and degradation properties of the fiber [7] Gowthaman et al. (2018). These fibers are inexpensive and are majorly eco-friendly. They are biodegradable; however, they are used with latex coating in certain open applications [8]. Fiber is the most often utilized soil reinforcing material. It is regarded as a useful strategy for improving soil strength, reducing swelling potential, and increasing liquefaction resistance. The ease of mixing, the availability of high strength qualities, and higher uniform strength distribution are advantages of using dispersed fiber threads to reinforce soil. Soil reinforcing techniques that mix chemical additives like cement, lime, fly ash, and polymers with randomly dispersed short fibers are likely to have a bright future. Compressive strength of the soil was greatly enhanced by the cumulative influence of fiber reinforcement and polymer treatment [9]. Compacted cement-fiber-sand mixtures outperformed pure cement mixtures in terms of flexural efficiency [10]. The addition of fibers to soil raises both peak and residual shear strength as well as unconfined compressive strength (UCS). In accordance with the results of the consolidation test, fiber content increases result in a decrease in the compression index (C_C) and the coefficient of volume change (C_V). Moreover, as the amount of fiber content rises, the rate of settlement does too [11]. Understanding the interactions and relations between soil particles, fibers, and chemical additives, as well as the possible effect of fiber characteristics (geometrical and strength) on the benefits of soil reinforcement, is vital for full scale implementation assessments of this combined approach.

Through the successful integration of coir fiber in the soil and enhancement with various proportions of coir pith and coir fiber (0-3% and 0-1%, respectively), through static triaxial, compaction, and California Bearing Ratio (CBR) tests, soft expansive subgrade soil was enhanced. The reinforced soil's compaction qualities and modulus were greatly enhanced by the coir fiber treatment [12]. The introduction of short fibers, such as glass, basalt, and polypropylene, affected the mechanical properties of the polyurethane-reinforced fine sand. Introducing 0.8% polypropylene fibers increased the reinforced soil's strength properties and flexibility parameters by nearly 108.07% and 295.42%, respectively [13]. A dependable and

efficient method to increase the ductility of soil is to incorporate fiber reinforcements into it. It is simple to create soil composites with randomly dispersed fibers because the fires prevent weak points from developing parallel to orientated reinforcement. Due to the lower cost of fly ash and natural fibers compared to cement stabilisation, lime stabilisation using these two materials is more cost-effective [14].

The paper presents a study that has adopted jute and coir for stabilizing soft clay. These fiber types are adopted as they have significant difference in their bio-chemical properties. Numerous studies have demonstrated the upsides of fiber additions to soil. In the current study, jute and coir fibers (natural fibers) are used to modify soft soil to determine their impact on the soil's plasticity and compressibility characteristics. The soft soil has been reinforced with 0%, 0.5%, 1%, 1.5%, 2% and 2.5% of jute and coir fibers. The index, compaction, UCS, and consolidation properties of the virgin and modified soil have been investigated. The outcomes demonstrated a reduction in the liquid limit (LL) and plasticity index (PI) as well as an increase in the plastic limit (PL) and shrinkage limits (SL) following the application of both jute and coir, demonstrating an improvement in the plasticity properties. Additionally, the reinforced soft soil's consolidation characteristics significantly improved.

This study's objective is to assess and contrast the plasticity properties of unreinforced or virgin soil with those of jute- and coir-modified soil. Also, to observe any change in the compaction as well as in compressive strength characteristics with the increasing content of fiber percentage in soil. The soil being highly compressible indicates the need to evaluate consolidation characteristics for a particular percentage of coir and jute and comparing it with the consolidation characteristics of virgin or unreinforced soil.

2. Materials and Methodology

2.1 Materials

2.1.1 Soft soil

The soft soil used in this study was procured from the Pallikaranai area of Chennai, Tamil Nadu, India. The soil was selected as a representative soft, fine-grained soil for evaluating its response to geotextile reinforcement. Enough soil was collected from the site and transported to the laboratory. The collected soil was initially air-dried under open sunlight for 3-4 days to remove excess moisture. After drying, the soil was pulverized carefully to break down soil lumps and achieve a relatively uniform consistency. The prepared soil was then stored in air-tight containers for further testing. The prepared soil sample was subjected to X-ray diffraction (XRD) analysis to determine the mineralogical composition. The characteristic diffraction peaks were analyzed and compared with standard reference patterns for the identification of the major crystalline minerals present in the soil. The XRD analysis provided the mineralogical characteristics of the unreinforced soft soil and established a reference for the evaluation of any mineralogical alterations induced by the subsequent treatment or reinforcement. Laboratory tests were carried out to determine the physical and engineering properties of soft soil such as specific gravity, particle-size distribution, Atterberg limits and compaction characteristics. The measured properties of the unreinforced soft soil are presented in Table 1, providing the baseline characteristics for comparison with the fiber-reinforced soil. The

mineralogical composition of the soft soil was determined using XRD analysis, which identified the major crystalline phases present in the soil [15]. The associated diffraction pattern is shown in Figure 1.

Table 1 Properties of soft soil

Properties	Values	Standard
Specific Gravity (G)	2.70	[16]
LL, %	82	
PL, %	42	[17]
PI, %	40	
SL, %	11.3	[18]
Max Dry Density, KN/m^3	13.71	[19]
Optimum Moisture Content, %	29.7	
UCS (Axial Stress), KPa	54.47	[20]
UCS (Failure Strain), %	7.79	

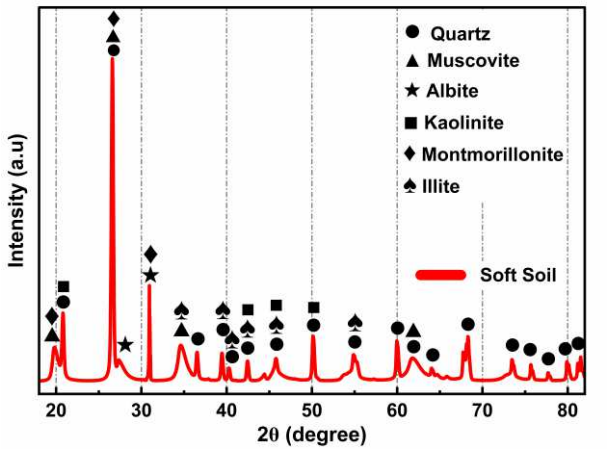


Fig. 1 XRD pattern for soft soil

The SEM micrograph of the soft soil without reinforcement is shown in Figure 2. The microstructure shows irregularly and flaky clay particles loosely packed with distinct interparticle voids and pores. The soil is soft, very plastic and compressible. The soil has relatively low strength as the particles are dispersed and have a porous fabric which indicates weak bonding between the particles [21].

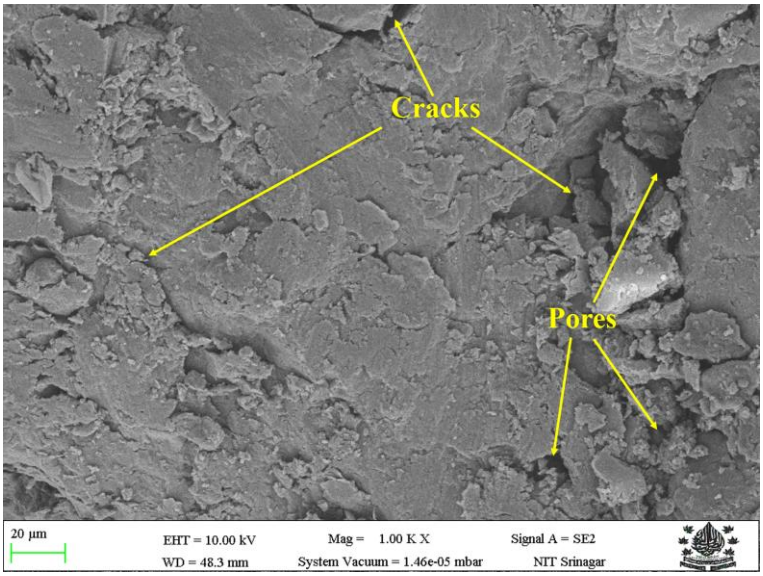


Fig. 2 SEM image for soft soil

2.1.2 Natural fibers

In the present study, jute and coir were used as reinforcement materials, which are natural fibers. Both the fibers were collected from a local dealer at Chennai, Tamil Nadu, India. The fibers were chosen due to their natural origin, availability, biodegradability, and potential in improving the mechanical response of soft soils through reinforcement. The procured fibers were visually examined to remove impurities, foreign materials and damaged portions. They were subsequently cleaned and dried under ambient conditions prior to use in the experimental program The jute and coir fibers were then cut to the required dimensions and prepared as per the predetermined reinforcement configuration. The obtained fibers were stored dry until use in soil specimens to ensure uniformity in testing. The mechanical and biochemical properties are shown in Table 2 and Table 3.

Table 2 Mechanical Property of Jute (Subhankar Biswas et al; 2013)

Type of Fiber	Density (g/cc)	Young's Modulus (GPa)	Ultimate Tensile Strength (MPa)	Moisture Absorption (%)
Coir	1.4	3.79	165-222	130-180
Jute	1.5	28.43	331-414	12

Table 3 Biochemical Properties of Jute (Sivakumar etal;2018)

Type of Fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Coir	32-43	21	40-45
Jute	56-71	29-35	11-14

XRD patterns of the coir and jute fibers are shown in Figure 3(a,b). The coir fiber shows a typical diffraction peak at about 22.64° (2θ) that is attributed to the (002) crystallographic plane of cellulose with other lower intensity reflections at 15.95° and 34.12° (2θ) that correspond to the (101) and (004) planes respectively [22]. In comparison, the jute fiber shows the highest-intensity peak at approximately 22.7° (2θ), corresponding to the (200) crystallographic plane

of cellulose, while lower-intensity peaks at approximately 15.92° and 34.7° are associated with the (110) and (004) planes, respectively, indicating the presence of cellulose I (native cellulose) [22]. The characteristic reflections confirm the semicrystalline nature of both fibers, with crystalline cellulose domains embedded within an amorphous matrix primarily comprising hemicellulose and lignin.

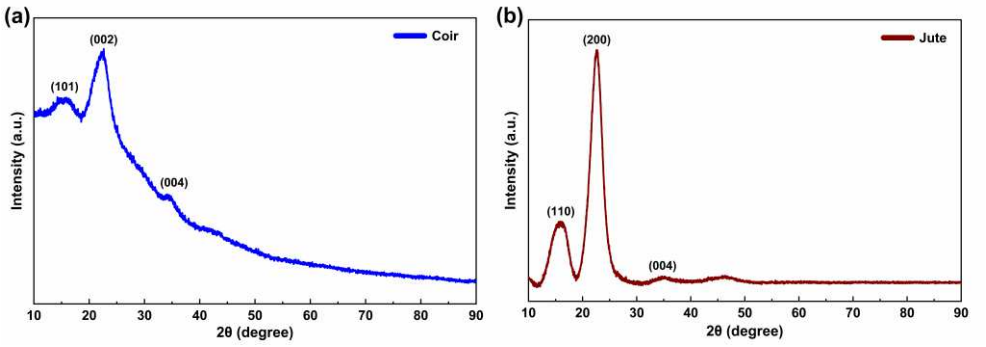


Fig. 3 XRD pattern for (a) Coir, and (b) Jute

2.2 Methodology

2.2.1 Experimental Program

The experimental program was designed to investigate the influence of natural fiber reinforcement on the engineering behaviour of soft soil. Two naturally available fibers, coir and jute, were used as reinforcement. The diameter from SEM analysis for coir and jute fiber threads at average was evaluated as 200 micrometer and for jute fiber threads was 66.5micrometer as shown in Figure 2. With the Length/Diameter ratio chosen for coir of 50 and for jute of 150, the appropriate Length/Diameter ratio was calculated for both coir and jute fiber threads at average equals 1 cm. The soil was then reinforced with fibers (cut in 1 cm threads) randomly oriented. The fiber content varied as 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% by total weight of the soil sample. An unreinforced soil specimen containing 0% fiber was considered as the control condition.

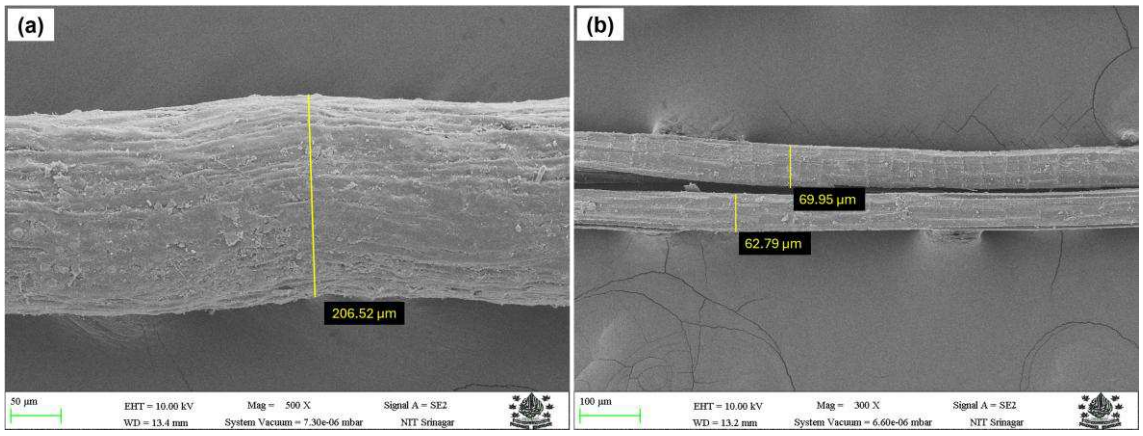


Fig 3. SEM analysis of fiber thread for (a) coir and (b) jute

For each fiber type, the required quantity of fiber was accurately weighed and uniformly mixed with the prepared soil to achieve the specified fiber content. The fibers were introduced into

the soil gradually and thoroughly mixed to minimize fiber clustering and to obtain a relatively uniform distribution throughout the soil matrix. The reinforced soil mixtures were subsequently subjected to laboratory testing to evaluate changes in their index, compaction, strength, and consolidation characteristics. The experimental results obtained at different fiber contents were compared with those of the unreinforced soil to determine the optimum fiber content (OFC) and identify the most effective natural fiber for improving the engineering behaviour of the soft soil.

2.2.2 Laboratory investigation of unreinforced/reinforced soft soil

The plasticity, compaction, UCS, and one-dimensional consolidation properties of the unreinforced and fiber-reinforced soil were determined following the relevant ASTM standards. The LL, PL, and PI were evaluated in accordance with ASTM D4318 [17], while the SL was determined according to ASTM D4943/D4943M [18]. The compaction characteristics, including maximum dry density (MDD) and optimum moisture content (OMC), were determined using the mini-compaction method reported by Sridharan and Sivapullaiah (2005) [19]. The UCS was determined in accordance with ASTM D2166/D2166M [20], and the one-dimensional consolidation characteristics were evaluated following ASTM D2435/D2435M. These tests were conducted to assess the influence of varying jute and coir fiber contents on the engineering behaviour of the soft soil.

3. Results and discussion

3.1 Physical and Engineering properties

3.1.1 Atterberg's Limits

The addition of natural fibers significantly altered the consistency characteristics of the soft soil. As shown in Figure 4, the LL of the unreinforced soil was 82.00%, which decreased with increasing fiber content. For coir-reinforced soil, the LL decreased to 75.37%, 74.60%, and 74.31% at 0.5%, 1.0%, and 1.5% coir, respectively, representing a maximum reduction of 9.38% at 1.5% coir. A slight increase was observed thereafter, with LL reaching 74.50% and 74.84% at 2.0% and 2.5% coir, respectively. Similar reduction was observed in the LL of the jute reinforced soil from 78.14% at 0.5% to a minimum of 76.98% at 2.0% which corresponds to a reduction of 6.12% in comparison to the unreinforced soil. The next rise to 77.04% on 2.5% jute was marginal. The relatively higher LL values of jute reinforced soil may be attributed to higher water absorption and water retentivity capacity of jute fibers.

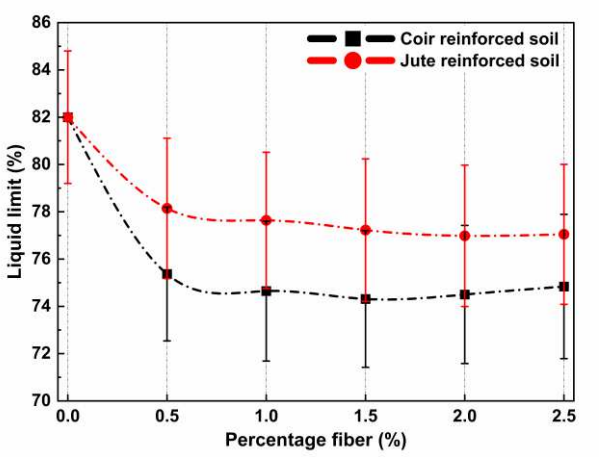


Fig 4. Variation of LL with increasing percentages of coir and jute fibers

As shown in Figure 5, the PL increased after the addition of the fiber. The PL of unreinforced soil was 42.00% which increased to 44.52-45.29% for coir reinforced soil and 45.13-46.27% for jute reinforced soil. The maximum PL was registered at 1.0% coir (45.29 %) and 1.5% jute (46.27 %) which showed an increase of 7.83% and 10.17% over the unreinforced soil respectively. The inclusion of fiber resulted in an increase in the moisture content required for the soil to reach its state of plasticity which can be attributed to the hydrophilic nature of the natural fibers and its ability to absorb water within the soil-fiber matrix.

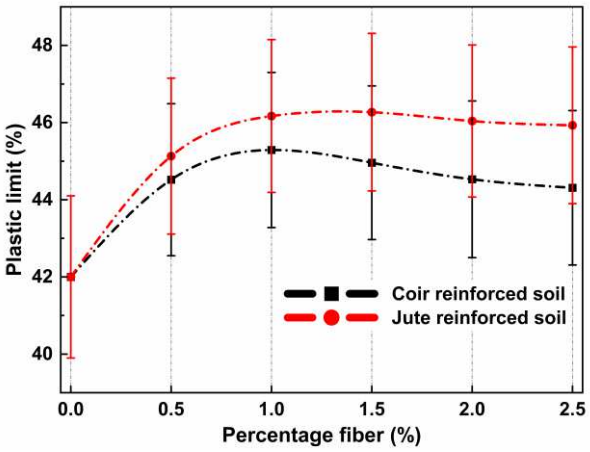


Fig 5. Variation of PL with increase in percentage of coir and jute fibers

The combined reduction in LL and increase in PL resulted in a substantial decrease in PI as seen in Figure 6. The PI for soft soil was found to be 40.00% which reduced to 30.85%, 29.31%, 29.35%, 29.97% and 30.53% with the addition of 0.5-2.5% coir respectively. The minimum PI of 29.31% at 1.0% coir shows a reduction of 26.73% in comparison to unreinforced soil. The PI for jute decreased from 33.01% at 0.5% to 31.46%, 30.95%, and 30.94% at 1.0%, 1.5%, and 2.0% before slightly increasing to 31.11% at 2.5%. Therefore, maximum reduction in PI for jute was 22.65% at 2.0% fiber content. Both fibers decreased the plasticity of the soft soil, with coir showing a higher decrease in PI than jute, indicating a more pronounced modification of the soil consistency characteristics.

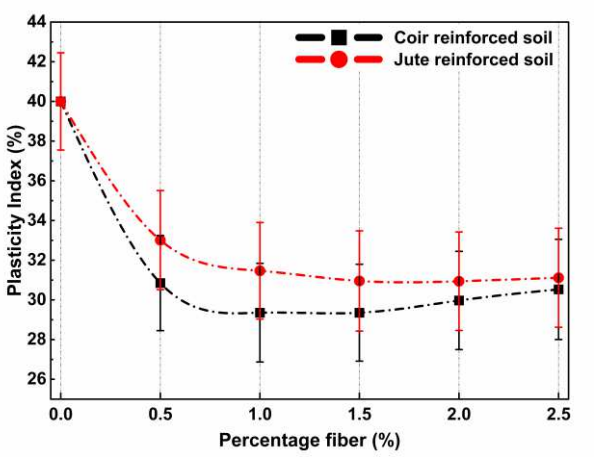


Fig 6. Variation of PI with increase in percentage of coir and jute fibers

3.1.2 SL test

The variation of SL with the addition of coir and jute fibers is shown in Figure 7. The SL of unreinforced soil was 11.28% and it increased steadily with the addition of fiber up to 2.0% fiber content. For soil reinforced with coir, the SL was 12.66% with 0.5% coir which increased to 13.45%, 14.24% and 15.18% with 1.0%, 1.5% and 2.0% coir respectively. The maximum increase was 34.57% with 2.0% coir. A marginal reduction to 14.83% was observed at 2.5% coir. The same pattern was observed for jute-reinforced soil with an increase in SL from 13.08% at 0.5% to 14.30%, 15.46%, and 16.52% at 1.0%, 1.5%, and 2.0% to a slight decrease of 15.68% at 2.5%. The maximum SL of 16.52 % at 2.0 % jute is related to an increase of 46.45 % when compared with the unreinforced soil.

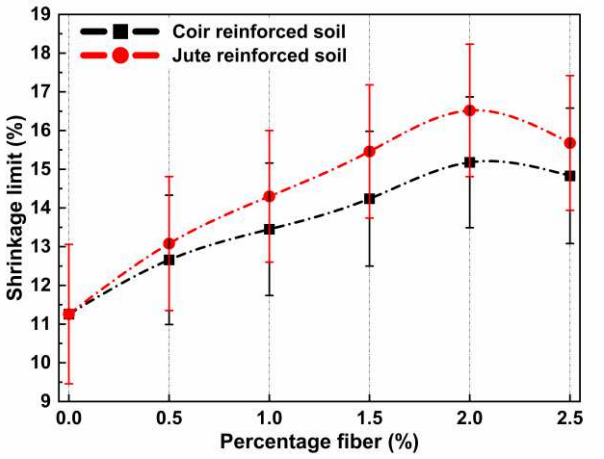


Fig 7. Variation of SL with increasing percentage of coir and jute fibers

The increase in SL suggests that the fiber inclusion increased the water content below which no significant volume reduction occurs during further drying. The observed behavior can be explained in terms of the water retention capacity of the natural fibers and the formation of a soil-fiber network that limits the particle rearrangement and excessive volumetric contraction during drying. Jute showed a higher SL than coir at all the respective fiber contents, which indicates a relatively higher effect on the shrinkage characteristics of the soil. However, the decrease observed above 2.0% fiber content indicates that excess fiber addition could lead to

less uniform distribution of the fibers and less effectiveness of the reinforcement network. The maximum SL was obtained for both coir and jute at 2.0% fiber content, in general, which indicates the beneficial effect of fiber content on the shrinkage behavior of soft soil.

3.1.3 Compaction characteristics

The effect of coir and jute fiber reinforcement on the compaction characteristics of the soft soil was studied in terms of MDD and OMC. The variation of MDD and OMC with fiber content is shown in Figure 8(a,b). The MDD of the unreinforced soil was 13.71 KN/m^3 and OMC was 29.70%. With the addition of coir fibers, the MDD increased progressively from 14.37 KN/m^3 at 0.5% to 15.62 KN/m^3 at 2.5%, corresponding to an overall increase of 13.93% compared with the unreinforced soil. The OMC, however, decreased from 29.70% to 27.31% for 1.5% coir, representing an 8.05% reduction, followed by a slight increase to 28.13% at 2.5%.

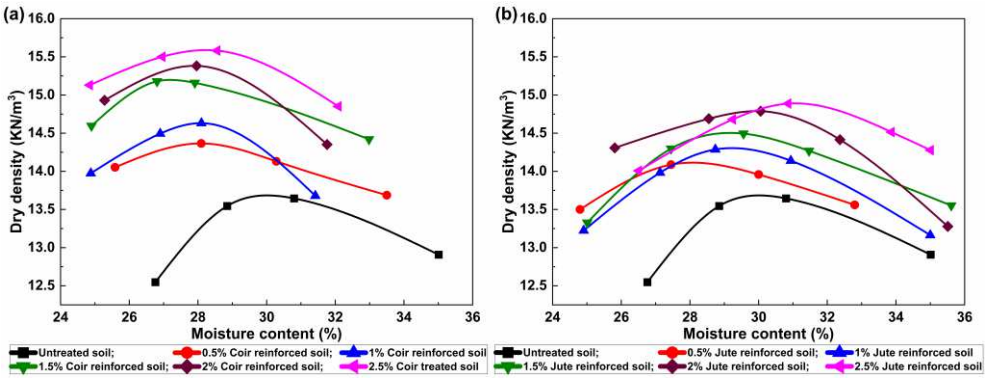


Fig 8. Compaction curve for (a) Coir reinforced soil, and (b) Jute reinforced soil

A similar increasing trend in MDD was observed for jute-reinforced soil, although the magnitude of improvement was lower than that observed with coir. The MDD increased from 14.12 kN/m^3 for 0.5% to 14.88 kN/m^3 for 2.5% jute, representing a 8.53% increase relative to the unreinforced soil. In contrast, the OMC of jute-reinforced soil showed a gradual increase from 28.03% at 0.5% to 30.61% at 2.5%. The OMC initially remained close to that of the unreinforced soil and increased beyond 1.0% fiber content, with the maximum increase of 3.06% occurring at 2.5% jute.

The enhancement of MDD with fiber addition might be due to better interlocking of particles and rearrangement of soil particles around fibers during compaction, leading to a denser soil–fiber matrix. The more pronounced increase observed for coir, may be associated with the differences in fiber geometry, surface texture and interaction with soil particles. The lower OMC of the reduced OMC with the lower coir content shows the better packing of the particles, whereas the increase in OMC at the higher coir content can be attributed to the higher water holding capacity and the additional voids created by the fibers. The progressive increase in OMC for jute can be associated with its relatively higher moisture absorption capacity. Overall, the results showed that coir improved the MDD more than jute, while the OMC response depended strongly on both fiber type and fiber content.

3.1.4 UCS test

Figure 9 shows the effect of coir and jute fiber reinforcement on the UCS of soft soil. The unreinforced soil developed an axial stress of 54.47 KPa at an axial strain of 7.79% . The axial strength increased significantly with the inclusion of natural fibers, although response was fiber type- and fiber content-dependent. For coir reinforced soil the axial stress increased from 67.21 KPa to 78.95, 92.95 and 97.34 KPa for 0.5%, 1.0%, 1.5% and 2.0% coir respectively. The maximum axial stress of 97.34 KPa at 2.0% coir represents a 78.62% increase over the unreinforced soil. However, a reduction to 94.15 KPa was observed at 2.5% coir, indicating that further fiber addition beyond 2.0% did not provide additional strength improvement. The corresponding axial strain increased from 7.05% at 0.5% to a maximum of 10.25% at 2.0%, demonstrating improved deformation capacity of the reinforced soil.

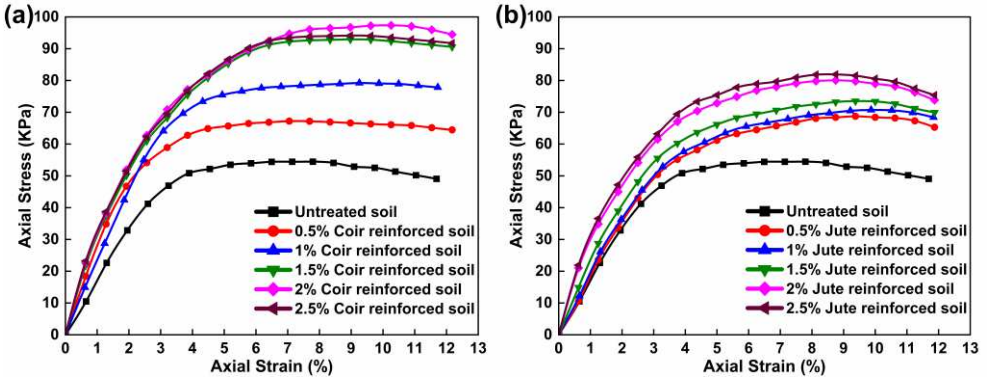


Fig 9. Variation of axial stress with axial strain for (a) Coir, and (b) Jute reinforced soil

Jute reinforcement also enhanced the axial strength, with the axial stress increasing from 68.41 KPa at 0.5% to 70.73, 73.52, 80.06, and 81.82 KPa at 1.0%, 1.5%, 2.0%, and 2.5% jute, respectively. The maximum axial stress of 81.82 KPa at 2.5% jute corresponds to a 50.21% improvement compared with the unreinforced soil. In contrast to coir, the strength of the jute-reinforced soil continued to increase with fiber content over the investigated range. The axial strain decreased progressively from 10.00% for 0.5% to 8.75% for 2.0% and 2.5%, indicating a change in the deformation response with increasing jute content.

The improvement in UCS can be attributed to the tensile resistance, frictional interaction, and mechanical interlocking developed between the soil particles and randomly distributed fibers. The fibers act as reinforcing elements that bridge potential failure surfaces and restrict the development and propagation of shear-induced deformation. The higher strength enhancement obtained with coir, particularly at 2.0% fiber content, may be attributed to its surface texture and good interaction with the soil matrix. The addition of excess fiber beyond the optimum coir content may cause fiber clustering and reduced soil-fiber contact, limiting further strength improvement.. Overall, 2.0% coir produced the highest UCS improvement, whereas the strength of jute-reinforced soil increased progressively up to the maximum investigated content of 2.5%.

3.1.5 Consolidation characteristics

To ascertain the initial impact of the fibers on the consolidation characteristics or parameters and the potential for future research on such problematic soil with varying fiber contents, the consolidation test was conducted with soil samples that were reinforced with 1% coir and 1.5% jute. For consolidation, the virgin and fiber-reinforced soil samples were subjected to surcharge pressures of 50, 100, 200, 400, 800, and 1600 KPa. The compressibility parameters were measured based on the time-settlement data measured for the reinforced and unreinforced soil.

A plot of dial reading and logarithmic time was made to determine the time correlating to 50% consolidation, which was then used to calculate the coefficient or rate of consolidation (C_V) for every pressure augmentation by using equation 1 given below:

$$C_v = 0 \cdot 197 \frac{d^2}{t_{50}} \quad (1)$$

The results showed that a higher C_V value of $1.4992*10^{-3}$ cm^2/sec at a high normal stress of 1600 KPa was observed when jute was incorporated in soft soil, and the C_V rate of coir-modified soil reported smaller value of $1.3095*10^{-3}$ cm^2/sec at a high normal stress of 1600 KPa as compared to jute-reinforced soil. As a result, reinforced soil has a higher Coefficient of Consolidation (C_V) value than fiber-reinforced soil. Even at the initial loads of 50 KPa, the rate of consolidation for unreinforced soil was very low ($4.0467*10^{-4}$ cm^2/sec) as compared to the coir-reinforced soil ($7.2602*10^{-4}$ cm^2/sec) and jute-reinforced soil ($8.3230*10^{-4}$ cm^2/sec). The alteration of the C_V with varying stress is shown in Figure 10. In the construction phase, lower CV values may result in protracted consolidation. Although the consolidation test has been carried out with 1% coir and 1.5% jute fiber, the results need to be further substantiated with a higher percentage of fiber.

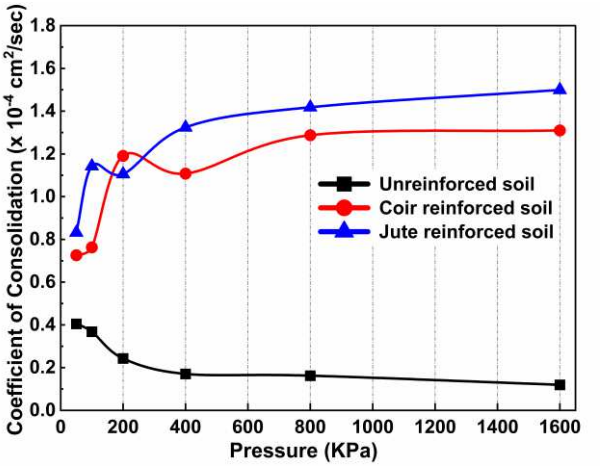


Fig 10. Curves of coefficient of consolidation versus pressure for unreinforced, and coir and jute reinforced soft soil

The void ratio variation of a soil reinforced with coir and jute is depicted in Figure 11. When soil was reinforced with jute fiber, the void ratio increased significantly. Even though the void ratio in both the coir and jute-reinforced soils decreased significantly, the soil had improved.

In all cases, the initial and final void ratios decreased as the load increased (whether reinforced or unreinforced soil).

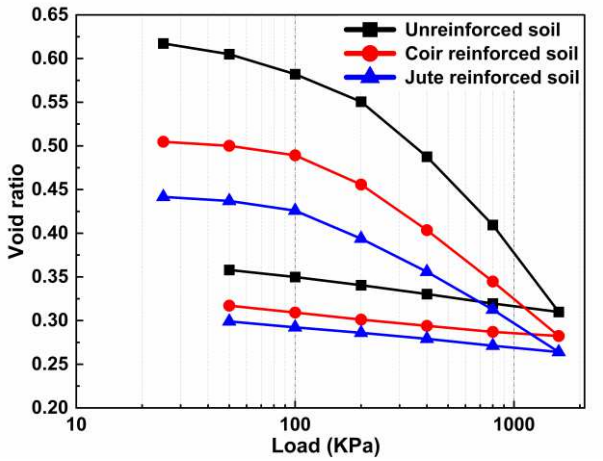


Fig 11. Comparative representation of variation of void ratio with varying loads for unreinforced, coir reinforced and jute reinforced soft soil

The C_C is used to gauge how compressible clays are. The C_C is the inverse of a semilogarithmic void ratio vs. logarithmic normal stress or load plot. The results of C_C show a significant decrease in values when soil is reinforced with coir and jute and so did swelling index (S_I) and coefficient of compressibility (a_V). For coir-reinforced soil, the C_C decreases in comparison to the unreinforced soil by nearly 72%, and similarly, for jute-reinforced soil, it decreases by nearly 69%. The consolidation values are depicted in Table 4. The rearrangement of soil particles and their adhesion to the fibers are the causes of this decrease. Therefore, increasing the closure of fibers and soil grains results in densification of the soil sample and hence improvement in consolidation. This is also attributed to decrease in water content, and an improvement in the consistency and void ratio.

Table 4. Consolidation characteristics for unreinforced and coir and jute reinforced soft soil

Consolidation Property	Unreinforced	Coir Reinforced Soil	Jute Reinforced Soil
C_C	0.4328	0.1229	0.1350
S_I	0.0540	0.0235	0.0234
C_V, m^2/kN	$1.58*10^{-4}$	$1.1385*10^{-4}$	$1.08*10^{-4}$
a_V, m^2/kN	$3.2575*10^{-4}$	$1.8501*10^{-4}$	$1.3547*10^{-4}$

3.2 Microstructural Analysis

3.2.1 X-Ray Diffraction

The X-ray diffraction (XRD) patterns of the unreinforced soft soil, coir-reinforced soil, and jute-reinforced soil are presented in Figure 12. The unreinforced soil exhibits a mineral assemblage comprising quartz, kaolinite, albite, illite, muscovite, and montmorillonite, which is characteristic of clay-rich soils containing both non-expansive and expansive clay minerals. Quartz is the dominant crystalline phase, as evidenced by the intense reflection at approximately 26.6° (2θ), together with additional quartz peaks at 20.8°, 36.5°, 39.5°, 42.5°, 50.1°, 54.9°, 60.0°, 68.5°, 74.1°, 76.1°, and 80.4°. The presence of clay minerals is confirmed

by kaolinite peaks at 21.2°, 43.0°, 46.1°, and 50.0°, albite reflections at 27.8° and 30.9°, illite peaks at 35.0°, 43.1°, 46.1°, and 55.2°, muscovite reflections at 19.8°, 27.8°, 35.0°, and 62.0°, and montmorillonite peaks at 19.8°, 27.2°, 31.0°, 35.0°, 39.3°, 43.0°, and 55.2°.

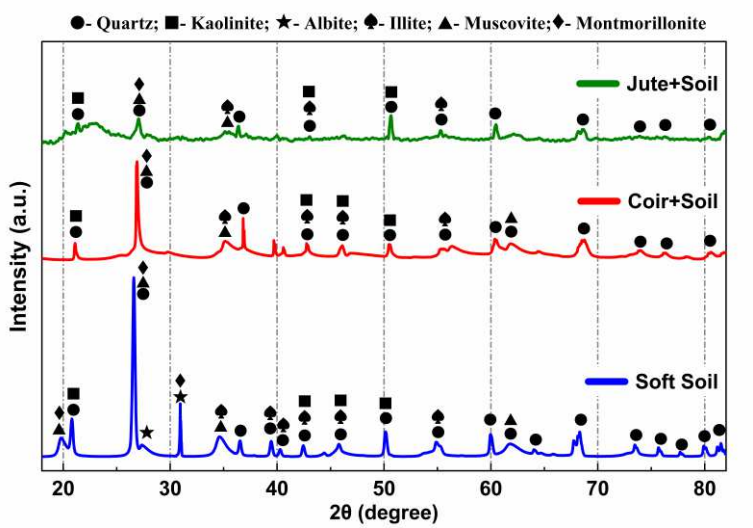


Fig. 12. XRD pattern of soil mixed with fibers (Coir and Jute)

The addition of coir fiber did not lead to the formation of new crystalline phases; hence the reinforcement was attributed to physical interaction rather than chemical modification of the soil minerals. The characteristic quartz peak at 26.6o was the dominant reflection while the peaks of kaolinite (43.0°, 46.1° and 50.0°), illite (35.0°, 43.1°, 46.1° and 55.2°), muscovite (35.0° and 62.0°) and montmorillonite (27.2°, 35.0° and 55.2°) were preserved. A few reflections from clay minerals showed minor changes in peak intensity and broadening indicative of changes in the packing of the particles and the soil-fiber interface rather than in the crystal structure. The changes observed are in agreement with the reduction in LL and PI and enhancement in compaction attributes for the coir reinforced specimens.

Similarly, the jute-reinforced soil retained the same mineralogical phases as the unreinforced soil, with prominent quartz reflections at 26.6°, 36.5°, 42.5°, 50.1°, 54.9°, 60.0°, 68.5°, 74.1°, 76.1°, and 80.4°. The persistence of kaolinite (21.2°, 43.0°, and 50.0°), illite (35.0°, 43.1°, and 55.2°), muscovite (27.8° and 35.0°), and montmorillonite (27.2° and 55.2°) confirms that the original mineral framework remained unchanged after reinforcement. Compared with the unreinforced soil, slight variations in the relative intensities of the clay-mineral peaks indicate improved soil aggregation and redistribution of particles around the fibers, which can enhance frictional resistance and stress transfer within the soil matrix.

The lack of other diffraction peaks in both the reinforced soils proves that the coir and jute fibers do not chemically react with the soil minerals during the reinforcement. The observed improvements in plasticity, compaction and UCS are instead attributed primarily to mechanical interlocking, fiber bridging and enhanced frictional interaction between randomly distributed fibers and soil particles. The XRD results thus corroborate the observed engineering performance by validating that the reinforcement mechanism is primarily physical and retains the inherent mineralogical characteristics of the soft soil.

3.2.2 Scanning Electron Microscopy (SEM) of reinforced soil

The microstructural features of the coir and jute reinforced soils are shown in Figure 13(a,b). The SEM micrographs reveal that the two natural fibers are well embedded in the soil matrix in which they are in intimate contact with the surrounding soil particles. The fibers adhere to the surfaces of the particles and wrap around individual soil grains, forming a continuous reinforcing network that connects neighbouring particles. This soil-fiber interaction enhances particle interlocking and improves stress transfer thru the soil matrix.

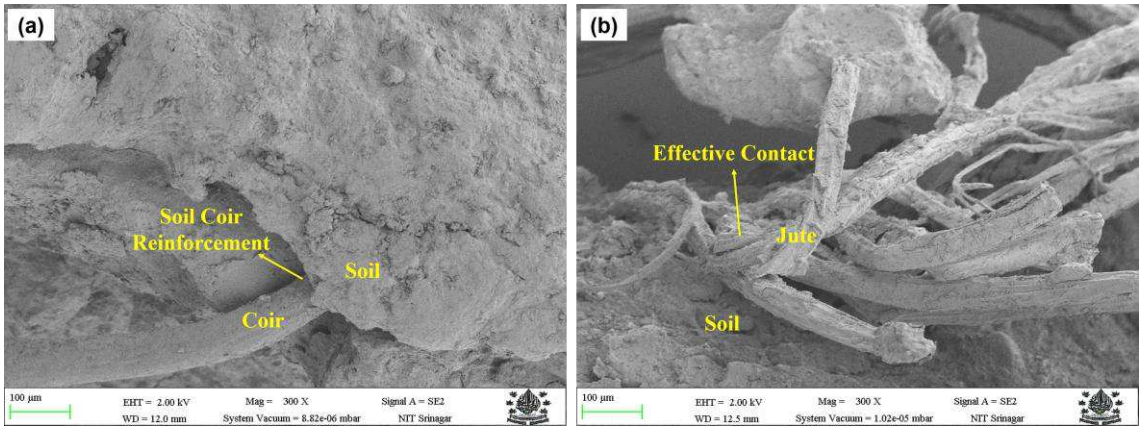


Fig 13. SEM for (a) coir reinforced soil and (b) jute reinforced soft soil

The presence of coir and jute also resulted in a denser microstructure compared to unreinforced soil. SEM images reveal that fibers are filling the interparticle voids and restricting the separation of soil particles, thus decreasing pore spaces and creating a denser soil fabric. The rough surface texture of the fibers also enhances the frictional resistance at the fiber-soil interface, enhancing the anchorage in the matrix and limiting the particle displacement under loading.

The microstructural evolutions observed are consistent with the experimental results obtained from the engineering tests. The increase in MDD and improvement in UCS after fiber reinforcement can be explained by improved particle interlocking and reduction in void ratio. Likewise, the formation of a three-dimensional reinforcement network prevents deformation and crack propagation, which leads to the decrease in plasticity and enhancement in deformation characteristics in both coir and jute reinforced soils. The SEM observations, in general, confirm that the reinforcement mechanism is mainly controlled by fiber bridging, mechanical interlocking and frictional interaction, which altogether improve the structural integrity of the soil matrix.

The overall results demonstrated that both coir and jute fibers were effective in enhancing the engineering behavior of soft soil, but their performance differed according to the property being assessed. Fiber reinforcement decreased LL from 82.0% to 74.31% (1.5% coir) and 76.98% (2.0% jute), increased PL to 45.29% (1.0% coir) and 46.27% (1.5% jute) and reduced PI up to 26.73% for coir and 22.65% for jute. SL increased from 11.28% to 15.18% (2.0% coir) and 16.52% (2.0% jute) which shows improved volumetric stability. Moreover, the compaction characteristics showed an improvement, as the MDD increased from 13.71 kN/m^3 to 15.62 kN/m^3 for coir and 14.88 kN/m^3 for jute while the OMC showed a decreasing trend for coir

and a gradual increase for jute. The UCS test showed the maximum strength improvement where the axial stress was increased from 54.47 KPa for unreinforced soil to 97.34 KPa at 2.0% coir and 81.82 KPa at 2.5% jute. XRD analysis indicated that the addition of fibers did not change the mineralogical composition of the soil. SEM observation showed improved particle interlocking, fiber bridging and fewer pore spaces in the soil matrix. The overall macro and micro scale results indicate that the natural fibers reinforcement improves the soil stability mainly through physical reinforcement mechanisms. The coir fiber with 2.0% showed the most favorable overall improvement in engineering performance whereas jute showed comparatively better resistance against shrinkage.

Conclusions

The present investigation reveals the potential of coir and jute fibers as sustainable reinforcement materials for improving the engineering behavior of expansive soft soil. The experimental results indicate that the inclusion of natural fibers is effective in improving the soil's plasticity, strength, compaction and consolidation properties. The primary findings are:

1. Fiber reinforcement improved the consistency properties of the soft soil by decreasing the LL up to 8% (coir) and 5% (jute), increasing the PL up to 8% (coir) and 10% (jute) and reducing the PI by 27% and 22%, respectively. SL increased from 11.28% to 15.18% for 2% coir and 16.52% for 2% jute indicating improvement in volumetric stability and reduction in settlement potential.

2. Coir reinforcement gave higher MDD of 15.62 kN/m^3 and reduced OMC while jute gave higher MDD of 14.88 kN/m^3 with gradual increase in OMC. Higher MDD with coir indicates better particle packing and denser soil matrix during compaction.

3. Fiber reinforcement improved the UCS of the soft soil significantly. The maximum axial stress of 97.34 KPa was observed at 2% coir, whereas it was 81.82 KPa at 2.5% jute. The better performance of coir indicates its higher effectiveness in increasing the soil resistance to compressive loading before failure.

4. The consolidation behavior of the soft soil improved significantly due to fiber reinforcement. The compression index was reduced from 0.4325 to 0.1229 and 0.1350 for coir and jute, respectively. This corresponds to a reduction of 72% and 69%, respectively. The coefficient of consolidation (C_v) increased by up to 105% for 1.5% jute and 80% for 1% coir at 50 KPa, while the a_V decreased from $3.257*10^{-4}$ m^2/kN to $1.850*10^{-4}$ m^2/kN (coir) and $1.354*10^{-4}$ m^2/kN (jute) indicating reduced settlement and improved load-bearing performance.

Therefore, the incorporation of coir and jute fibers was effective in decreasing the LL, PI and compression index and increasing the SL, MDD, UCS and coefficient of consolidation of soft soil. The improvements suggest that natural fiber reinforcement can improve the plasticity, strength, and consolidation characteristics of the soft soil, thus providing a sustainable and effective method for stabilization.

Author contributions

Ansab Shafi Mir: Writing - original draft, Methodology, Formal analysis, Conceptualization.

Bhuvaneshwari S.: Review & editing, Investigation, Formal analysis.

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Data availability

Data will be made available on request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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