



Eco-engineered rice-husk nanosilica enhances soil structural stability and reduces detachment capacity in paddy fields

Misagh Parhizkar¹, Safoora Asadi Kapourchal², Masoumeh Izadpanah Nashroudkoli², Manuel Esteban Lucas-Borja³, Demetrio Antonio Zema^{4,*}

¹ Rice Research Institute of Iran, Agricultural Research, Education and Extension Organization (AREEO), Rasht 4199613475, Iran.

² Faculty of Agricultural Sciences, University of Guilan, Rasht 4199613776, Iran.

³ Department of Agroforestry Technology, Science and Genetics, School of Advanced Agricultural and Forestry Engineering, Campus Universitario s/n, Castilla La Mancha University, E-02071 Albacete, Spain.

⁴ AGRARIA Department, Mediterranean University of Reggio Calabria, Loc. Feo di Vito, I-89122, Reggio Calabria, Italy.

* Corresponding author. E-mail: dzema@unirc.it

Abstract: Previous studies have shown that silica nanomaterials produced from rice residues, such as husk, can influence several soil properties. However, their effects on soil detachment capacity and structural characteristics in rice paddy fields remain poorly quantified. This study evaluated the effects of nanosilica derived from rice husk on wet aggregate stability, plasticity index, and detachment capacity in paddy soils of Northern Iran under different flow discharges simulated in a hydraulic flume. The nanosilica used in this study was produced by acid extraction followed by controlled heating, and was incorporated into field plots at a 2% amendment level. Results showed that wet aggregate stability and plasticity index significantly increased by 32% and 27%, respectively, in the nanosilica-treated soils compared with the untreated control. Conversely, the average soil detachment capacity decreased by 49%, also in this case significantly. Multivariate analysis indicated strong interrelations among the measured properties and distinctly separated the amended soils from the control group. Linear regressions between detachment capacity and shear stress or stream power showed that nanosilica reduced soil erodibility and increased the threshold resistance to particle detachment under increasing flow power. Overall, the findings demonstrate that rice-husk-derived nanosilica enhances aggregate cohesion and substantially reduces soil vulnerability to concentrated flow erosion in paddy systems.

Keywords: Soil erosion; Wet aggregate stability; Soil plasticity index; Hydraulic forces; Rice husk nanosilica; Paddy soil.

1 INTRODUCTION

Soil erosion is one of the most significant threats to agricultural productivity (Derpsch et al., 2024). Often, particle detachment is enhanced by soil structure breakdown and dispersion due to overland flow (Zhou et al., 2021). In rice paddy soils subjected to prolonged flooding and drainage cycles (Wang et al., 2022), the degradation of soil structure is accelerated by repeated wetting and drying as well as by mechanical tillage, which cumulatively result in reductions in soil organic matter and nutrients (Jin et al., 2022). For instance, in Northern Iran, rice fields commonly remain fallow after harvest and are then exposed to intense seasonal rainfall for several months. Although field slopes are generally low, concentrated runoff may develop along wheel tracks, small drainage pathways, and micro-rills, promoting soil particle detachment and nutrient depletion (Parhizkar et al., 2020).

Structure degradation leads to increased susceptibility of soil particles to detachment due to raindrops and overland flow (Lu et al., 2016). As a result, soil fertility and water-holding capacity decline, reducing crop yield and ecosystem health. Soil amendment has been suggested and practised for a long time to tackle soil structure degradation and fertility decline, using a large variety of organic compounds (Jensen et al., 2016). Elucidating the role of soil amendments in enhancing aggregate stability and mitigating particle detachment under hydrodynamic stress is imperative for advancing sustainable management strategies within irrigated paddy ecosystems.

Recent developments in nanotechnology have introduced novel approaches for managing soil degradation in agricultural systems (Mridha et al., 2025). Among emerging nanomaterials, silica nanoparticles (SiO₂) have gained attention in agricultural research due to their high specific surface area, reactive surfaces, and chemical stability (Li et al., 2025; Yang et al., 2021). Upon incorporation into the soil matrix, nanosilica facilitates complex interactions with clay minerals, organic colloids, and exchangeable cations, thereby establishing robust interparticle bridging mechanisms that significantly augment overall soil structural integrity (Chaudhary et al., 2024). Furthermore, due to its surface reactivity, nanosilica drives the physico-chemical forces controlling particle cohesion, which in turn influences erosion resistance (Parhizkar et al., 2023; El-Ramady et al., 2022). In this context, eco-engineered nanosilica is relevant not only as a silicon source for crops (Kovács et al., 2022), but also as a potential soil-structuring agent capable of improving the strength of fine-grained soils (Thapa and Ghani, 2025) and reducing soil detachment under concentrated flow. This function is particularly important in paddy fields, where puddling, flooding–drainage cycles, and post-harvest rainfall can weaken aggregates and promote particle mobilisation in small rills, wheel tracks, and drainage pathways.

Agricultural residues can serve as feedstock for producing nanosilica, offering a sustainable route for generating functional nanomaterials while reducing biomass waste. Rice husk, an abundant by-product of rice milling (Hamada et al., 2025), represents an economical and widely available precursor for

producing amorphous silica used in soil improvement (Piyathissa et al., 2023). Rice husk-derived nanosilica shows excellent purity and surface activity, which makes this residue a cheap but effective substrate for soil amendment (Rakesh et al., 2025). Principles of circular economy models suggest the reuse and valorisation of nanosilica from rice husk in agriculture, especially in rice paddy fields.

Despite the growing interest in nanosilica applications, empirical evidence about its effects on soil structural stability and anti-erosive action in paddy ecosystems is still limited. In waterlogged rice paddies, flooding can cause large damage to rice fields (Van Rutten et al., 2025) by weakening bonding among soil aggregates. Conversely, periodic drainage induces cyclic desiccation and rehydration, triggering shrink-swell dynamics that exacerbate micro-fissuring and structural disintegration. Such processes predispose the soil to pronounced concentrated erosion, particularly within preferential flow paths and wheel-track incisions generated by mechanised tillage. Therefore, supplying and incorporating nanosilica from rice husk to paddy soils may stabilise aggregates by forming additional siloxane bridges (Zhang et al., 2014). Moreover, the influence of nanosilica on the so-called ‘Atterberg limits’, particularly the plasticity index (Kalhor et al., 2022), may positively influence soil cohesion. However, the extent to which these improvements translate into measurable reductions in detachment, especially in concentrated erosion, must be experimentally quantified in the field under variable hydraulic and morphological conditions. To the best of current knowledge, the potential of nanosilica to mitigate concentrated soil erosion in paddy environments has not yet been systematically investigated. Only Parhizkar (2025) examined nanosilica within a soil-plant system framework, with emphasis on rhizosphere processes, phosphorus uptake, root development, and associated changes in aggregate stability and erosion response.

This study advances that investigation by focusing on soil mechanical behaviour, analysing the relationships between detachment capacity and plasticity in paddy soils in northern Iran in comparison to untreated soils. Soil detachment capacity (D_c), commonly adopted as an indicator of soil resistance to concentrated erosion, has been measured in laboratory-based flume experiments under controlled hydraulic conditions. In this flume, the soil scouring mimics soil detachment in a large rill under controlled morphological and hydraulic conditions. The specific objectives of the study were: i) to characterise the extracted nanosilica using Fourier-transform infrared spectroscopy and field emission scanning electron microscopy; ii) to compare wet aggregate stability, plasticity index, and detachment capacity between nanosilica-treated and untreated paddy soils; iii) to identify associations among those variable using multivariate statistical analysis; and iv) to explore the relationships between detachment capacity and key hydraulic variables, including shear stress and stream power. By using nanosilica amendment within soil-mechanics principles, this study provides new insight into how eco-engineered nanomaterials enhance structural resilience and erosion resistance in intensively cultivated rice systems.

2 MATERIALS AND METHODS

2.1 Study area

Paddy fields in Sangar district of Guilan province (Northern Iran, 37°09'30.94" N; 49°40'34.56" E) were chosen as the study area (Fig. 1). The mean annual precipitation and temperature are 1448 mm/yr and 17.7 °C, respectively (Moloudi and Yaghmaeian Mahabadi, 2019). The mean altitude is 39 m above

the mean sea level, and the land slope is in the range of 1% to 3%. The soil has a clay loam texture, with average sand, silt, and clay contents of 27.3%, 35.0%, and 37.7%, respectively (SDSD, 2017). According to the available regional soil survey information, the soils in the study area are characterised by udic soil moisture and thermic soil temperature regimes. Geomorphologically, the area consists mainly of lowlands and alluvial plains developed over metamorphic, volcanic, and sedimentary parent materials (Izadpanah et al., 2025). Considering the long-term paddy management, repeated puddling, and seasonal flooding, the soil is an anthropogenically modified paddy soil and is consistent with the Anthroisol reference group in the WRB system. The main initial properties of the untreated soil are: soil moisture 31.3%; organic carbon 2.13%; bulk density 1.43 g cm⁻³; electrical conductivity 1.84 dS m⁻¹, and cation exchange capacity 31.91 cmol kg⁻¹.

Hashemi rice, a well-known traditional Iranian cultivar widely grown in Guilan province and within the study region (Rahmani and Mani-Varnosfaderani, 2022), dominates local paddy systems. This variety contains approximately 8.91% protein and 21.38% amylose (Feizollahi et al., 2018).

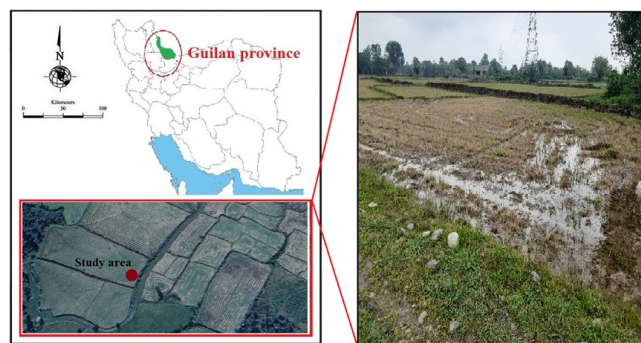


Fig. 1. Geographical location of the study area, aerial view and a picture of paddy fields under study (Sangar district, Guilan province, Northern Iran) (source: Google Map).

2.2 Silica nanoparticle production

Rice husk biomass was used as the precursor material for the preparation of silica nanoparticles following the acid-leaching and thermal treatment procedure reported by Sharma et al. (2019), with minor adaptations. The rice husk was first washed to remove adhering dust and soil particles and then treated with 10 wt% HCl for 2 h to dissolve metallic and mineral impurities. After acid treatment, the material was repeatedly rinsed with deionised water until the washing solution approached neutral pH, oven-dried at 100 °C for 24 h, and thermally treated at 700 °C to obtain silica-rich ash. The resulting powder was gently ground and sieved to obtain a homogeneous nanosilica material before soil application (Wang et al., 2012). The produced silica nanopowder was subsequently blended by hand into the surface soil layer of the experimental plots, which measured 1.3 m by 0.5 m with a depth of 0.1 m (Parhizkar et al., 2021; Parhizkar et al., 2023; Ricks et al., 2020). A 2 wt% application rate was selected in line with a previous study (Parhizkar, 2025), which identified this rate as a sufficient level to improve soil moisture retention, aggregate stability, and root-soil interactions without requiring excessive amendment input.

2.3 Soil sampling

After nanosilica incorporation into the surface soil layer, the amended plot was maintained under the local paddy management

conditions until post-harvest sampling. The seven-month interval between field application and post-harvest sampling selected in this study corresponded to a full rice-growing cycle in the study area and allowed nanosilica to interact with soil particles, roots, irrigation water, and wetting-drying phases under realistic paddy-field conditions (Parhizkar et al., 2023).

Following this interval, the field plot was partitioned into nine distinct sections. From each section, nine undisturbed soil cores were collected using a steel sampling ring (10 cm diameter, 5 cm height), following the procedures described by Zhang et al. (2008) and Parhizkar et al. (2025). An equivalent set of soil cores was obtained from an untreated plot to serve as the control, using the same sampling method. Of the nine cores collected from each section, seven were allocated to flume tests for determining soil detachment capacity under the different slope and discharge scenarios (see Section 2.5), while the remaining two were used to quantify key soil properties (see Section 2.8). This sampling arrangement enabled direct comparison between the hydraulic responses and mechanical attributes of the soil samples.

2.4 Measurement of soil properties

Wet aggregate stability was determined on 18 soil samples (9 samples $\times$ 2 experimental conditions, treated and control soils), randomly collected in the plot (Kemper and Rosenau, 1986). Moreover, the liquid (LL) and plastic (PL) limits of soil were determined on the same number of additional soil samples by the Casagrande plasticity chart method (Casagrande, 1948). Based on these values, the plasticity index (PI) was calculated.

2.5 Flume experiments

Soil detachment capacity (D_c) denotes the maximum rate at which soil particles can be removed from a surface by clear, sediment-free water when exposed to a defined hydraulic load. It is considered a fundamental descriptor of concentrated-flow erosion, as it characterises the intrinsic resistance of the soil to shear forces generated by flowing water. In the present study, soil detachment capacity (D_c) was determined using a laboratory hydraulic flume designed to simulate concentrated flow under controlled hydraulic conditions. The experimental setup consisted of a steel frame structure lined with PVC panels, forming a rectangular channel 3.0 m long and 0.20 m wide, with an adjustable bed slope.

Table 1. Values of the hydraulic variables measured in flume experiments to simulate the soil detachment capacity on soil samples collected in rice paddy fields (Sangar district, Guilan province, Northern Iran).

Experiment	Slope (S, %)	Water discharge (q , L s ⁻¹)	Water depth (mm)	Flow velocity (V , m s ⁻¹)
1	1.2	2.51	7.1	1.76
2		2.91	8.1	1.79
3		3.70	8.9	2.08
4	1.5	2.51	5.8	2.16
5		2.91	6.7	2.16
6		3.70	7.8	2.37
7	2.2	2.51	4.9	2.55
8		2.91	5.5	2.64
9		3.70	6.8	2.72

For each test, a soil core (10 cm in diameter and 5 cm in height) taken either from the nanosilica-treated plot or from the untreated control plot was positioned in the designated opening in the flume bed. Prior to the experiment, the soil surface was

moistened by continuous spraying for a period of 24 h. During the run, the following hydraulic variables were measured (Table 1): i) water discharge at the outlet, six times using a graduated cylinder; ii) surface velocity, nine times using a fluorescent dye tracer (the mean velocity was corrected using the coefficient of 0.67, suggested by Abrahams et al., 1985, for turbulent flow, based on Reynolds' number, over 2000); and iii) water depth, six times across two cross-sections, with three points per section, using a level probe connected to a digital measuring device. Before the experiments, the water-depth probe was checked for exact working. All measurements of water discharge, surface velocity, and water depth were repeated to ensure stable inflow conditions (Parhizkar, 2025).

Each detachment test was stopped when the depth of erosion within the steel ring reached approximately 0.015 m or when the experiment duration reached five minutes (Nearing et al., 1991; Zhang et al., 2002). After completion of the run, the soil sample was removed, oven-dried for 24 h at 105 °C, and subsequently weighed. The mean soil detachment capacity (D_c , kg s⁻¹ m⁻²) of each run was calculated by equation (1):

$$D_c = \frac{\Delta M}{A \cdot \Delta t} \quad (1)$$

where ΔM is the dry weight of detached soil (kg), A is the area of the soil sample (m²) and Δt is the experiment duration (s).

2.6 Experimental design

Soil detachment measurements were performed under nine hydraulic scenarios generated by combining three slope gradients (1.2%, 1.5%, and 2.2%) with three inflow discharges (2.5, 2.9, and 3.7 L s⁻¹). These nine combinations were selected to represent the gentle slopes commonly measured in local paddy fields and the concentrated-flow discharges that may occur during irrigation, drainage, and post-harvest rainfall events.

Each hydraulic configuration was replicated seven times, resulting in a total of 126 experimental runs. Accordingly, the experiment followed a factorial design including two soil treatments (nanosilica-amended and untreated), three slope gradients, three discharge levels, and seven replicates for each treatment–hydraulic combination.

2.7 Calculation of hydraulic variables

Previous studies have demonstrated that soil detachment capacity is influenced not only by intrinsic soil characteristics (Geng et al., 2021), especially aggregate stability (Parhizkar, 2024), but is also controlled by flow characteristics (Sedaghatkish et al., 2025). In studies of soil detachment capacity, shear stress and stream power (with its unit value, i.e., the value for unit cross-section width) are key hydraulic parameters, which respectively represent the force exerted by flowing water on soil particles and the rate at which energy is delivered to erode the soil matrix (Knappen et al., 2007; Govers et al., 2007).

These variables were calculated according to the following equations:

$$\tau = \rho g R S \quad (2)$$

$$\Omega = \rho g R S V = \tau V \quad (3)$$

$$\omega = S V \quad (4)$$

where ρ is the water density (kg m^{-3}), g is the acceleration of gravity (m s^{-2}), R is the hydraulic radius (m), S is the bed slope (m m^{-1}), and τ , Ω , and ω are measured in Pa, kg s^{-3} , and m s^{-1} , respectively.

The critical shear stress (τ_c , Pa) is a threshold value that defines the start of particle movement and detachment, identifying the transition from stable to erosive flow conditions (Lei et al., 2008; Shen et al., 2016). We determined τ_c as the intercept of a linear regression equation interpolating D_c (dependent variable) and the values of shear stress (independent variable), under the following form:

$$D_c = K_r(\tau - \tau_c) \quad (5)$$

where K_r is the erodibility parameter (s m^{-1}) and τ_c are the slope and intercept.

2.8 Statistical analysis

First, differences in D_c , water-stable aggregate stability, and plasticity index between nanosilica-treated and control soils were evaluated using t-tests ($p < 0.05$). The equality of variance and normal distribution, which are assumptions of the t-test, were checked by Levene's and Shapiro-Wilk's tests.

Then, a correlation analysis among the soil properties and soil detachment capacity was carried out, and the coefficients of correlation between each pair of these variables and their significance level were calculated.

Finally, Principal Component Analysis (PCA) and Agglomerative Hierarchical Cluster Analysis (AHCA) were applied to identify relationships between D_c and soil properties and to evaluate whether nanosilica-treated soils could be distinguished from the control based on these variables. To run PCA, Pearson's correlation matrix was first calculated from the original variables after standardisation. Based on this matrix, PCA calculated two uncorrelated variables (the first two Principal Components, PCs) (Lee Rodgers and Nicewander, 1988), which retain more than 90% of the variance of the original variables.

AHCA is a distribution-free ordination technique to group samples with similar characteristics by considering an original group of variables. Using this technique, the measurements were measured in clusters according to similarity criteria. Euclidean distance was used as the similarity-dissimilarity measure, and the Ward's method was used to group the measurements.

The statistical analysis was carried out using Origin(Pro), release 2025b (OriginLab Corporation, Northampton, MA, USA) software.

3 RESULTS

3.1 Soil properties

Nanosilica treatment significantly ($p < 0.05$) increased wet aggregate stability and plasticity indexes compared with the untreated control. In more detail, wet aggregate stability (WAS) increased on average from 0.39 ± 0.02 in the control soil to 0.52 ± 0.03 in the treated soil, whereas the mean plasticity index increased from $22 \pm 2.83\%$ to $28 \pm 2.50\%$. The liquid (LL) and plastic (PL) limits in treated soils were also higher compared to the control ($61.6 \pm 5.61\%$ and $35 \pm 3.04\%$, respectively, against $52.2 \pm 4.29\%$ for LL, and $30.2 \pm 2.54\%$ for PL) (Fig. 2).

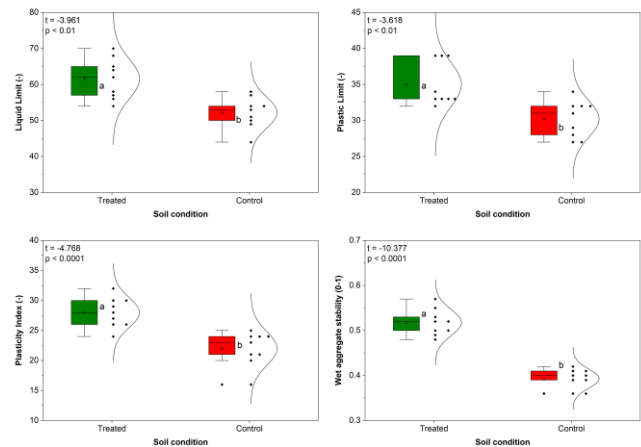


Fig. 2. Box-whisker plots ($n = 9$) of plasticity index and wet aggregate stability (0-1) measured on soil samples collected in rice paddy fields (Sangar district, Guilan province, Northern Iran) and treated with silica nanoparticles or untreated (control). Different letters indicate significant differences between the two soil conditions at $p < 0.05$.

3.2 Particle detachment capacity

Nanosilica treatment significantly ($p < 0.05$) reduced the soil detachment capacity compared with the untreated control. More specifically, the D_c was significantly lower ($p < 0.05$) in the treated soils ($0.151 \pm 0.05 \text{ kg m}^{-2} \text{ s}^{-1}$) compared to the control ($0.297 \pm 0.06 \text{ kg m}^{-2} \text{ s}^{-1}$) (Fig. 3). The distribution of detachment values also indicated lower variability in the nanosilica-treated soils than in the untreated control.

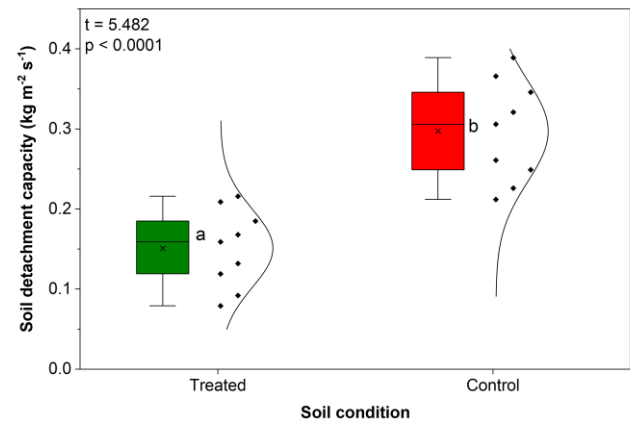


Fig. 3. Box-whisker plots ($n = 9$) of particle detachment capacity measured on soil samples collected in rice paddy fields (Sangar district, Guilan province, Northern Iran) and treated with silica nanoparticles or untreated (control). Different letters indicate significant differences between the two soil conditions at $p < 0.05$.

3.3 Relationships among soil properties and particle detachment capacity

The correlation analysis revealed strong negative relationships between D_c and all soil physical properties. The strongest correlation was noticed between WAS and D_c ($r = -0.85$), which was significantly associated with PL ($r = -0.62$), LL ($r = -0.54$), and PI ($r = -0.50$). Positive correlations were instead observed among all soil physical properties ($r > 0.46$), with a peak calculated between WAS and PI ($r = 0.75$) (Fig. 4).

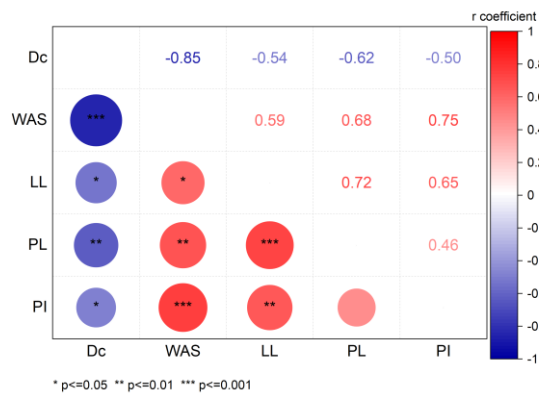


Fig. 4. Pearson's correlation matrix among pairs of soil properties and particle detachment capacity calculated on measurements made on soil samples collected in rice paddy fields (Sangar district, Guilan province, Northern Iran) and treated with silica nanoparticles or untreated (control). Legend: PC = Principal Component; Dc = particle detachment capacity; LL = liquid limit; PL = plastic limit; PI = plasticity index; WAS = wet aggregate stability.

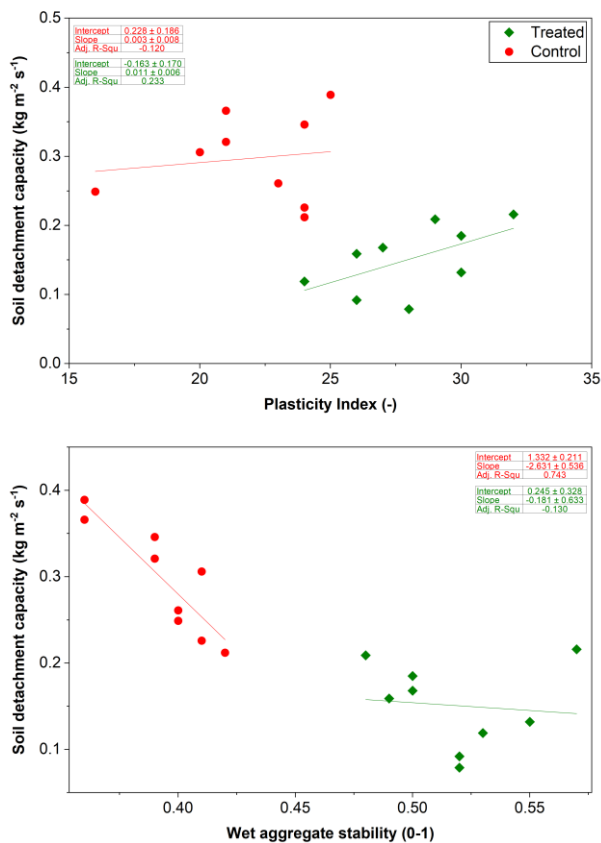


Fig. 5. Correlations between soil aggregate stability and plasticity index, and particle detachment capacity measured on soil samples collected in rice paddy fields (Sangar district, Guilan province, Northern Iran) and treated with silica nanoparticles or untreated (control).

With specific reference to the highest associations (D_c , and WAS and PI), the magnitude and direction of the correlation coefficients were consistent for both treated and untreated soils, but treated soils produced slightly stronger correlations due to reduced data dispersion. In more detail, D_c linearly decreases when WAS increases (R^2 equal to 0.71 for the treated soils and 0.75 for the control). The slope of both interpolating lines was

significantly negative between D_c and WAS, but the absolute value was lower for the treated soils compared to the control. These slopes, significantly positive, increased from treated to control soils in the interpolation between D_c and PL (Fig. 5).

The PCA calculated two principal components (PC1 and PC2) that explain 82.8% of the total variance in the original variables. PC1, alone accounting for 71.1% of the original variance, was strongly and positively influenced by WAS, LL, PL, and PI (loadings over 0.42), and negatively associated with D_c (-0.45). D_c and LL have noticeable loadings also on the PC2 (> 0.61), which, however, explains a minor share of the variance (11.8%) (Fig. 6a).

The sample distribution in the score plot of PCA shows two clearly distinct clusters along PC1. All nanosilica-treated soils are associated with positive PC1, and control soils are positioned in the negative quadrants for PC1. This evident grouping is confirmed by the analysis of the dendrogram provided by the AHCA (Fig. 6b). One cluster contains all treated soil samples (with only one exception), while the second cluster groups all control samples, without mixed grouping.

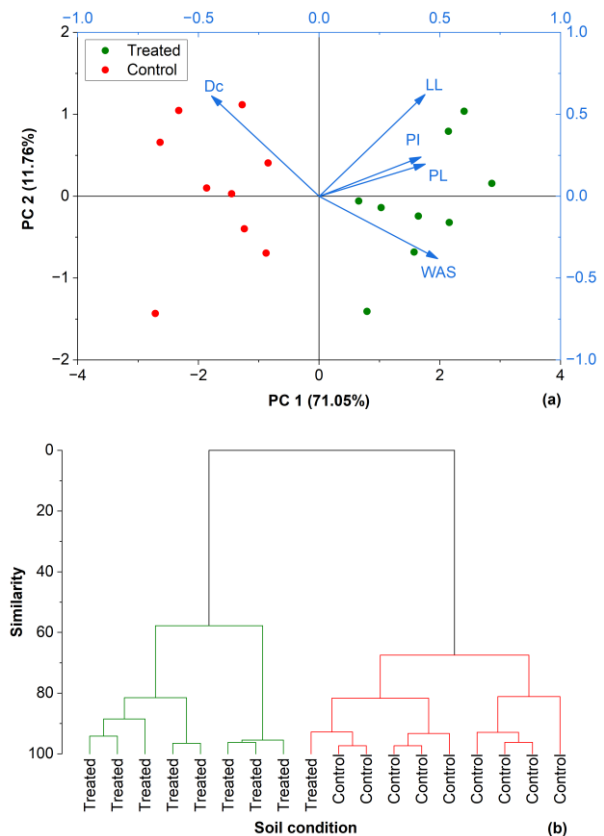


Fig. 6. Biplot of Principal Component Analysis (a) and dendrogram provided by the Agglomerative Hierarchical Cluster Analysis (b) applied to original variables (particle detachment capacity and soil properties) measured on soil samples collected in rice paddy fields (Sangar district, Guilan province, Northern Iran) and treated with silica nanoparticles or untreated (control). Legend: PC = Principal Component; D_c = particle detachment capacity; LL = liquid limit; PL = plastic limit; PI = plasticity index; WAS = wet aggregate stability. Different colours refer to different clusters.

3.4 Soil detachment response to hydraulic forces

The linear regressions between D_c and the three studied hydraulic variables - shear stress (τ), stream power (Ω), and unit stream power (ω) - are characterised by high coefficients of

determination for both treated and control soils (Fig. 7). The R^2 values were 0.72 for control and 0.66 for treated soils for the $D_c - \tau$ interpolation. The slope of the regression line, equal to the erodibility parameter (0.30 s m^{-1}), for treated soils was lower compared to the control (0.23 s m^{-1}), indicating lower sensitivity of treated soils to changes in shear stress. Also the critical shear stress - that is, the value of shear stress at which detachment begins - decreased from treated soils (0.32 Pa) to the control (0.01 Pa). The $D_c - \Omega$ regressions, with R^2 values exceeding 0.80, showed similar patterns as for $D_c - \tau$, treated soils exhibiting a lower slope for the interpolation line compared to the control. The $D_c - \omega$ plot reveals the strongest relationship among the three hydraulic parameters (R^2 of 0.88 for control and 0.87 for treated soils).

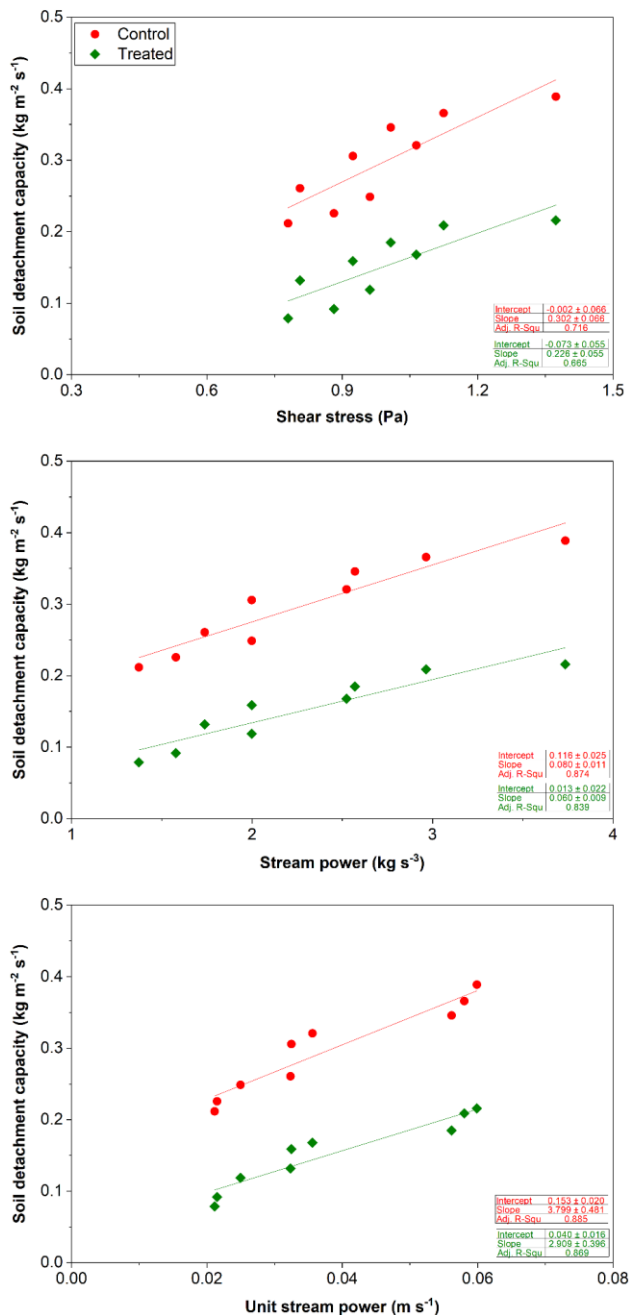


Fig. 7. Linear regressions between particle detachment capacity and shear stress (upper panel), stream power (mid panel), and unit stream power (lower panel) measured on soil samples collected in rice paddy fields (Sangar district, Guilan province, Northern Iran) and treated with silica nanoparticles or untreated (control).

4 DISCUSSION

Previous studies have shown that nanosilica derived from rice husk can provide high-purity amorphous silica with a large reactive surface area and gradual silicon release in soil systems (Wang et al., 2012; Piyathissa et al., 2023). In agricultural applications, nanosilica has been reported to improve soil water retention, nutrient availability, root development, and aggregate stability, although the magnitude of these effects depends on soil texture, application rate, and interaction time. For instance, Parhizkar (2025) reported that rice-derived nanosilica enhanced root development, phosphorus uptake, and soil stability in rice paddy conditions, whereas Parhizkar et al. (2023) showed that silica nanoparticles reduced rill detachment when used in combination with hydromulch. Nevertheless, quantitative information on whether these structural improvements reduce detachment capacity under defined hydraulic forces remains scarce. This study has advanced this knowledge by determining the changes in soil structural stability and resistance to detachment on a quantitative approach and at the laboratory scale.

4.1 Soil properties

With specific regard to soil properties, the observed enhancement in aggregate stability in the treated soils likely arises from chemical effects, namely nanosilica functioning as a reactive binding agent, which strengthens the connections between clay particles (Thomas and Kodi, 2020). These nanoparticles possess abundant silanol groups on their surfaces that facilitate condensation reactions with the hydroxylated edges of clay minerals, forming Si-O-Si linkages that reinforce the aggregate framework and improve the mechanical properties of both clayey soil and sandy soil (Gu et al., 2022). As a result, the soil matrix becomes more resistant to slaking and dispersion when exposed to repeated wetting, a critical property in flooded paddy environments.

The enhanced aggregate stability observed in the nanosilica-amended soil reflects not merely a physico-chemical alteration, but also a tangible mechanical reinforcement of the soil matrix. This effect is again of chemical origin, and derives from the negatively charged surfaces of nanosilica that interact with polyvalent cations such as Ca^{2+} and Mg^{2+} , enhancing flocculation (Romero et al., 2018) and reducing the repulsive electrostatic forces between particles. This process turns to physical improvements, supporting the development of microaggregates that, thanks to the coalescence into macroaggregates, improve porosity distribution and structural characteristics.

The approximately 30% increase in the plasticity of nanosilica-amended soils further indicates a physical, substantial modification of soil-water interactions within the fine-grained fraction. Both the plastic and liquid limits increase due to stronger bonding between mineral particles and an increase in the water adsorption capacity, respectively, through its high specific surface area and hydrophilic nature (Kalhor et al., 2019). Together, the elevated plasticity limits suggest that nanosilica-amended soils are more capable of withstanding mechanical disturbances, including tillage and water-induced shear, while maintaining structural integrity.

4.2 Particle detachment capacity

Concerning the interaction soil-water due to the overland flow, the consistent attenuation of particle detachment across a spectrum of discharge rates and slope gradients underscores the

structural resilience imparted to the soil matrix by nanosilica supplementation. Soil detachment capacity is directly associated with the critical shear stress required for starting the displacement of particles (Yan et al., 2024). The treated soils show higher resistance thresholds, which implies that greater hydraulic energy is needed to detach particles. This mechanical resistance derives from both improved aggregate bonding and increased cohesion between aggregates (Zhang et al., 2019). Consequently, even under higher flows, the treated soils are subjected to reduced sediment loss and surface degradation. These benefits are particularly appreciable in paddy soils, where frequent irrigation and drainage cycles often promote soil loss. The reduced detachment rates measured in this study agree with previous research showing that silica-based amendments can improve soil aggregation, consistency limits, and resistance to mechanical disturbance. For example, Gu et al. (2022) showed, at multiple observational scales, that nano-SiO₂ improved the mechanical properties of both clayey soil and sandy soil effectively. Kalhor et al. (2019, 2022) attributed this effect to the increased strength and cohesion of fine-textured soils due to the supply of nano-SiO₂. Parhizkar et al. (2023) found that silica nanoparticles used together with hydromulch improved root–soil interactions and reduced rill detachment capacity.

4.3 Relationships among soil properties and particle detachment capacity

The positive correlation between aggregate stability and plasticity index, revealed by the correlation analysis, suggests that the soil's capacity to undergo reversible deformation without particle detachment increases with plasticity, enhancing structural resilience. The strong negative correlations between detachment capacity and the measured soil physical properties highlight the central role of aggregate stability in governing soil resistance to particle detachment under hydraulic stress. The high magnitude of the correlation between D_c and WAS demonstrates that aggregate stability is an important factor controlling particle removal from the soil matrix (Nsabimana et al., 2023), particularly in soils subjected to frequent wetting-drying cycles. The consistent associations between PI, LL, and PL also suggest that nanosilica enhances the water adsorption capacity of soil, which, in turn, reinforces the soil matrix.

These relationships were supported by the multivariate analyses, which clearly discriminated treated from untreated soils. This separation demonstrates that aggregate stability, plasticity, and detachment capacity are closely interrelated, with nanosilica acting as a unifying amendment that simultaneously enhances the mechanical stability and hydraulic resistance of paddy soils.

The incorporation of nanosilica extracted from rice husk exerted a noticeable influence on the structure, plasticity, and resistance to detachment of the studied paddy soils. This response can be interpreted through three complementary mechanisms: chemical bonding, physical reinforcement, and hydraulic resistance. Chemically, the abundant silanol groups present on nanosilica surfaces can interact with hydroxylated clay mineral edges (Lagaly et al., 2013) and soil colloids, favouring the formation of Si–O–Si and Si–O–Al linkages and strengthening interparticle contacts. Physically, the high specific surface area and nanoscale size of the particles may promote interparticle bridging and cation-mediated flocculation, particularly in clay loam soils where reactive clay surfaces and polyvalent cations provide suitable bonding sites. These processes increase wet aggregate stability and reduce the

tendency of aggregates to slake and disperse under repeated wetting. From a hydraulic perspective, the stronger aggregate framework increases the threshold force required for particle mobilisation (Parhizkar et al., 2026), which explains the lower detachment capacity and higher critical shear stress observed in the nanosilica-treated soils.

4.4 Soil detachment response to hydraulic forces

The linear regressions between soil detachment capacity and the hydraulic variables, selected to interpret the morphological and hydraulic conditions of soil detachment, demonstrate that kinetic energy of flow is an important driver of particle removal due to overland flow (Firoozi and Firoozi, 2024). These regressions also indicate that the treated soils show a lower sensitivity to increasing hydraulic forces compared to the control samples. This is quantitatively highlighted by the reduction in the slope of the $D_c - \tau$ and $D_c - \Omega$ relationships as well as by the higher values of the critical shear stress. Therefore, it is further confirmed that soil detachment increases with hydraulic forces less in treated soils compared to the samples in the absence of treatment and that nanosilica increases the threshold force required to initiate particle mobilisation (Aksu and Eskisar, 2023).

The high coefficients of determination of all regressions depend on the strong interaction between hydraulic actions and soil mechanical response across different flow discharges and soil gradients simulated by the flume experiments. The highest value of R^2 of the $D_c - \omega$ interpolation confirms that unit stream power can better capture the effects of flow velocity and depth on soil detachment compared to the other variables (Parhizkar et al., 2020).

4.5 Study limitations, future research and practical implications

Despite the promising results obtained in this study, some limitations should be acknowledged. First, the experiments on soil detachment with and without nanosilica treatment were carried out in a small-scale flume. These experimental devices allow controlled hydraulic and morphological conditions but do not capture the variability in climatic, hydrological and geomorphological conditions, which influence the detachment process. Future studies should validate the laboratory-scale results of this study by field trials and long-term monitoring in real conditions.

Second, only one soil type, nanosilica application rate, and interaction period were considered in this study. Therefore, the results should be interpreted as evidence for the tested clay loam paddy soil under the selected amendment rate and experimental conditions, rather than as a universal response for all paddy soils. Future studies should therefore test multiple soil types and nanosilica rates (on which the magnitude of improvement may depend), and longer monitoring periods (which may confirm whether the treatment is durable or exerts its action only for the short time) under both laboratory and field conditions. The additional tests on nanosilica effects could give land managers and agronomists insight into the most effective combination of doses and receiving soils to maximise the anti-erosive effects of nanosilica addition. Its possible long-term persistence in the soil may minimise the need for frequent reapplication, thereby reducing maintenance costs.

Third and finally, because pore size distribution was not directly measured, any potential effect of nanosilica on soil pore arrangement should be considered as a plausible mechanism

rather than a demonstrated result. Future studies should combine detachment measurements with direct pore-structure analyses such as X-ray microtomography, mercury intrusion porosimetry, or water-retention modelling.

In spite of these limitations, the implications of this study are important towards the potential feasibility of nanosilica as a soil-protective agent in erosion-prone agricultural landscapes. Compared with conventional soil stabilisers such as synthetic polymers, lime, cementitious binders, gypsum, or imported commercial amendments, rice-derived nanosilica may offer an environmentally attractive option in rice-producing regions because the feedstock is locally abundant and often treated as an agricultural waste (Dzulhijjah et al., 2025). Farmers or local cooperatives could potentially integrate rice husk valorisation into existing rice-milling chains, although safe production of nanosilica requires controlled combustion, acid washing, quality control, and appropriate handling procedures. However, before recommending large-scale adoption, future work should evaluate production costs, field-scale application methods, environmental safety, persistence in soil, and the agronomic performance of repeated applications.

5 CONCLUSIONS

This study demonstrates that eco-engineered rice-husk nanosilica enhances the structural resilience of paddy soils by improving wet aggregate stability and plasticity characteristics and by increasing resistance to hydraulic detachment under variable flow discharge and slope conditions. While earlier research highlighted rhizosphere-mediated improvements, the present findings indicate that rice-husk-derived nanosilica can also improve soil-mechanical indicators related to consistency, aggregation, and resistance to hydraulic detachment. The application of rice husk-derived nanosilica significantly enhanced the mechanical and hydraulic properties of paddy soils. The treated soils showed higher aggregate stability (on average +30%) and plasticity index (+28%) as well as a lower soil detachment capacity (-50%) under variable flow discharge and soil slope. These improvements can be ascribed to the formation of siloxane linkages and enhanced interparticle bonding induced by the nanosilica. Multivariate statistics revealed that all these properties were significantly correlated with each other, which means that soil treatment with nanosilica improves the structural and plastic characteristics of soil and reduces its sensitivity to particle detachment. The linear regressions between particle detachment and key hydraulic variables demonstrated that nanosilica reduces the soil erodibility and enhances the critical shear stress with increasing flow power.

Overall, the study demonstrates that the use of rice-husk-derived nanosilica valorises agricultural waste and provides a feasible option to reinforce soil structure and mitigate erosion in irrigated rice paddy fields. Future studies should explore long-term and field-scale anti-erosive effects of nanosilica together with the optimal doses at variable soil and climatic conditions.

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Supplementary materials

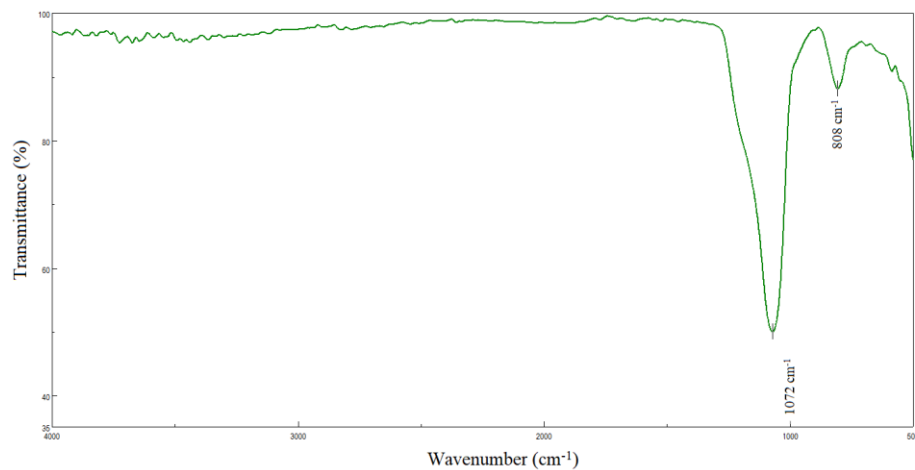


Fig. 1SM. Fourier-Transform InfraRed (FTIR) spectroscopy of nanosilica extracted from rice husks.

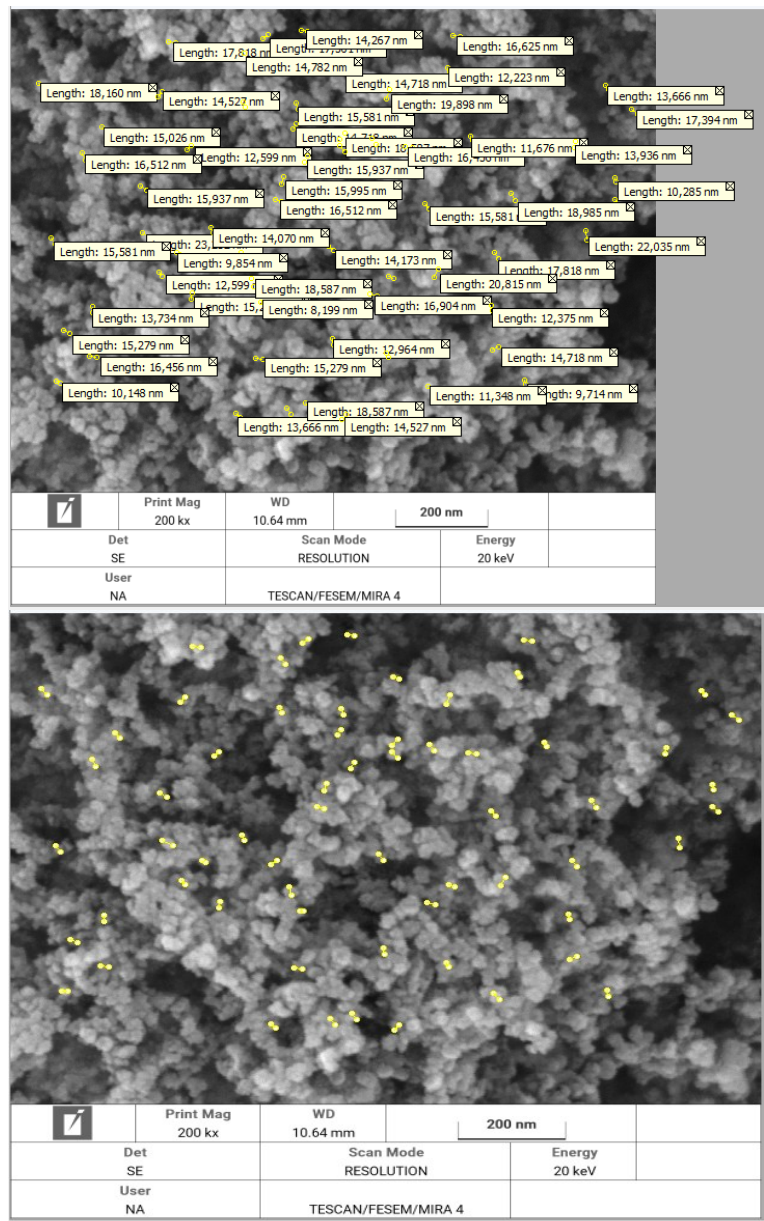


Fig. 2SM. Field Emission Scanning Electron Microscopy (FESEM) analysis of nanosilica extracted from rice husks.

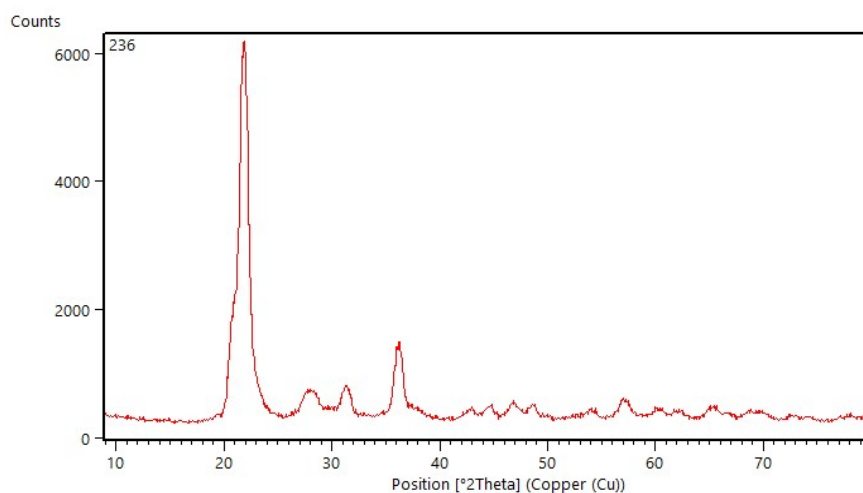


Fig. 3SM. X-Ray Diffraction (XRD) pattern analysis of nanosilica extracted from rice husks.

Table 1SM. Composition of silica nanoparticles derived from rice husks.

Chemical compounds	Percentage
Al_2O_3	0.44
Fe_2O_3	0.14
SiO_2	98.45
CaO	0.13
K_2O	0.84
<i>L.O.I</i>	0.00

Notes: Al_2O_3 = aluminium oxide; Fe_2O_3 = ferric oxide, SiO_2 = silicon dioxide; CaO = calcium oxide; K_2O = potassium oxide; and L.O.I = loss on ignition.