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Immediate Soil Responses to Rice Straw Burning in Northern Iran's Farmlands

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ABSTRACT

Aims: Rice straw burning is a common practice in northern Iran. Therefore, examining its short-term effects on the physical and chemical properties of paddy soils in northern Iran is critical. The purpose of this study lies in its immediate pre–post fire sampling design, the use of PCA-based minimum data set (MDS) for SQI determination, and the development of a predictive SQI model tailored for paddy soils exposed to residue burning.
Materials & Methods: Soil samples were collected from the top 0–5 cm of burned and unburned paddy fields, after harvest. Several physicochemical indicators were analyzed, including organic Carbon (OC), soil moisture (SM), pH, electrical conductivity (EC), bulk density (BD), cation exchange capacity (CEC), and soil texture. The Soil Quality Index (SQI) was calculated from PCA-selected soil properties.
Findings: Soil properties showed significant changes following rice straw burning. OC and SM decreased sharply by approximately 33% and 34%, respectively, whereas pH and EC increased significantly by 13% and 56% ($p < 0.01$). These outcomes demonstrate that dynamic soil properties are more sensitive to burning than stable ones.
Conclusion: Burning rice straw impacts the topsoil of paddy fields by decreasing organic Carbon and soil moisture, while increasing pH and electrical conductivity. These changes cause a notable decline in the Soil Quality Index. Sustainable practices such as residue incorporation, composting, mulching, and soil moisture management are recommended to preserve soil health. These findings provide field-based quantitative evidence of the immediate degradation of soil quality caused by rice straw burning.

Keywords: Fire; Organic Carbon; Paddy Fields; Soil Moisture; Soil Quality Index.

CITATION LINKS

[1] Hashim N., Mohd Ali M., Mahadi M.R... [2] Mohidem N.A., Hashim... [3] Chen X., Shen R., Pan B., Peng Q.,... [4] Li S., Lu Z., Zhao J., Luo M., Che... [5] Food and Agriculture Organization ... [6] Mahdavi S.M., Mohammadian M., Mahd... [7] Limmer M.A., Linam F.A., Seyfferth... [8] Singh L., Brar B.S. A review on ri... [9] Kamboj A., Sadh P.K., Chawla P., S... [10] Tung N.S., Cu N.X., Hai N.X. Impact of rice... [11] Certini G. Effects of... [12] Kumar A., Kushwaha K.K., Singh S., Shivay Y... [13] Tripathi S., Singh R.N., Sharma S.K. Quanti... [14] Ademe Y.A. Long-term impacts of cultivation... [15] Wang G., Zhu T., Zhou J., Yu Y., Petropoulo... [16] Pradhan P., Sinha A.K., Pandit T.K. The eff... [17] Arunrat N., Sereenonchai S., Hatano R. Effe... [18] Arunrat N., Kongsurakan P., Solomon L.W., S... [19] Parhizkar M., Lucas-Borja M.E., Zema D.A. E... [20] Thomaz E.L., Antoneli V., Doerr S.H. Effect... [21] Zema D.A., Parhizkar M., Plaza-Alvarez P.A.... [22] Cheng Y., Luo P.,... [23] Baur M.J., Friend A.D., Pellegrini A.F.A. W... [24] Kooch Y., Nouraei A., Wu D., Francaviglia R... [25] Fox D.M., Darboux F., ... [26] Mohammadi Galangash M., ... [27] Yıldırım A. The stubble burning problem in ... [28] Abdurrahman M.I., Chaki S., Saini G. Stubbl... [29] Prosdocimi M., Jordan A., Tarolli P., Keess... [30] Prosdocimi M., Tarolli P., ... [31] Moloudi A., Yaghmaeian Mahabadi N. Quantita... [32] Soil Survey Staff. ... [33] Kottek M., Grieser J., Beck C., Rudolf B., ... [34] Rahmani N., Mani-Varnosfaderani A. Quality ... [35] Feizollahi E., Mirmoghtadaie... [36] Parhizkar M., ... [37] Navidi M., Lucas ... [38] Ryan K.C. Dynamic... [39] Arunrat N., Sereenonchai S., Sansupa C., Ko... [40] Gee G.W., Bauder J.W. Particle-size analysi... [41] Walkley A., Black I.A. An examination of th... [42] Hesse P.R. Textb. ... [43] Radcliffe D.E., Simunek J. Soil Phys. Hydru... [44] Chapman H.D. Cation exchange capacity. In: ... [45] Andrews S.S., Karlen D.L., Mitchell J.P. A ... [46] Wander M.M., ... [47] Lucas-Borja M.E., Parhizkar M., Zema D.A. S... [48] Ozlu E., Arriaga F.J., ... [49] Lucas-Borja M.E., Zema D.A. Short-term effe... [50] Granged A.J., Zavala L.M., Jordan A., Barce... [51] Jhariya M.K., Singh L. Effect of fire sever... [52] Halder M., Ahmad S.J., ... [53] Six J., Paustian K. ... [54] Ribeiro Filho A.A., Adams C., Manfredini S.... [55] Abebe Nigussie A.N., Kissi E.K. Impact of b... [56] Asgari H.R., Saiedyfar... [57] Fonseca F., de ... [58] Pellegrini A. F. A., ... [59] De Paul Obade, V.P., Lal, R. A standardized... [60] Chaer G.M., Myrold D.D., Bottomley P.J. A s... [61] Rostayee F., Kooch Y., Hosseini S.M. Soil q... [62] Sedaghatkish F., ... [63] Xu L., Yu Q., Bai S., Wang M., Sun W., Xu S... [64] Parhizkar M., Shabanpour M., Lucas-Borja M.... [65] Pena S.B., Schaik... [66] Kacergius A., Gegeckas A., Gudiukaitė R. Re...

Introduction

Rice is a primary staple food worldwide and provides an important source of nutrition for a large proportion of the global population [1]. It plays a vital role in agriculture and economies across numerous countries, particularly in Asia, where population projections indicate that the region will require approximately 8×10^6 t of rice annually [2]. Most rice paddy fields are located in Asia, and among the major rice-producing countries, India and China are the two largest [3,4]. Iran, a major rice producer in the Middle East, is expected to increase production by 18% in 2024, reaching about 2.6×10^6 t [5]. Most cultivation occurs in Northern provinces, including Guilan, Mazandaran, and Golestan, where the climate favors optimal growth [6].

Globally, rice production generates straw residues [7], presenting both significant challenges and opportunities for sustainable agricultural management. In response to these challenges, burning rice straw is a common, environmentally detrimental practice used for rapid field preparation [8,9]. Burning these residues results in significant alterations in soil properties, including a substantial reduction in microbial biomass and diversity [10]. The intense heat raises soil temperatures, reduces the abundance of key beneficial microorganisms such as bacteria and fungi, and alters the composition of microbial communities [11,12]. Furthermore, soil Nitrogen, phosphorus, and organic matter contents decrease by residue burning [13], while Potassium content often increases. This nutrient imbalance compromises soil fertility, as changes in soil characteristics, such as pH, can over time increase or decrease nutrient availability [14,15,16]. Beyond its local impacts, rice straw burning contributes to regional air pollution, greenhouse gas emissions, and the production of short-lived climate forcers, making it a growing environmental concern across Asia and other rice-producing regions. Understanding the immediate soil responses to residue burning is therefore critical not only for local soil management but also for developing sustainable residue management strategies aligned with climate-smart agriculture.

Many studies have demonstrated the negative impacts of fire on soil characteristics and health [17, 18, 19, 20], particularly in the upper soil layers [21]. Fire can cause Carbon loss [22], accelerate soil moisture loss [23], and increase bulk density and reduce porosity [24]. These changes highlight the immediate physical effects on soil structure [25]. Despite the prevalence of rice straw burning in northern Iran, especially Guilan Province [26], short-term effects on soil physicochemical properties remain poorly understood [16]. Understanding these immediate effects is essential because short-term changes in soil properties can significantly affect crop productivity and long-term soil health. However, few studies have quantified these impacts in northern Iran. Stubble burning reduces soil fertility and deteriorates soil structure, potentially increasing erosion [27]. Alternative management strategies, such as incorporating residues into soil or using them as fuel, have been suggested to mitigate these effects [28]. This study combines immediate pre- and post–fire sampling with PCA-based MDS and a predictive SQI model to provide a quantitative assessment of short-term soil responses to rice straw burning.

This study examined changes in various soil properties and overall soil quality between burned and unburned soils in rice paddy field systems. The decline in soil quality has been the primary outcome of recent practices, making these paddy fields suitable for this research. Previous studies show that leaving plant residues on the soil surface immediately after agricultural disturbance or fire significantly improves soil protection. The use of straw mulch has been widely reported as an effective method for limiting erosion, reducing runoff, and minimizing water loss through evaporation shortly after application across different agroecosystems [29]. Furthermore, an extensive review by Prosdocimi et al. [30] demonstrated that using vegetative mulches consistently enhances soil physical structure and hydrological performance by conserving soil moisture and organic matter.

Although the positive effects of straw mulching are well established, the burning of crop residues is still commonly practiced in rice-based agroecosystems, especially in northern Iran. The lack of quantitative information on the short-term consequences of this practice on soil quality underscores the need to evaluate the immediate soil degradation induced by straw burning, thereby providing a scientific basis for promoting alternative residue management strategies such as straw mulching in paddy fields. Understanding the immediate effects of rice straw burning is crucial for improving soil management practices.

The specific aims of the current study are to assess the short-term impacts of rice straw burning on soil physicochemical properties and to evaluate overall soil quality using the Soil Quality Index, including the development of a predictive SQI model for immediate post-fire soil conditions. The findings of this investigation can identify the risks associated with rice straw burning in paddy fields and suggest appropriate management practices to minimize anticipated impacts. We hypothesize that burning rice straw reduces soil quality by altering key topsoil properties: organic Carbon and soil moisture decrease, while pH and electrical conductivity increase, leading to an overall decline in the Soil Quality Index. This study aims to provide a preliminary understanding of the short-term effects of fire on soil properties and to establish a basis for modeling fire impacts and maintaining soil health in paddy fields.

To the best of our knowledge, this is among the first studies to combine an immediate pre–post fire sampling design with a PCA-based Soil Quality Index and predictive SQI modeling specifically for paddy soils affected by rice straw burning. However, quantitative evidence on the immediate post-fire effects of rice straw burning on paddy soils in northern Iran remains limited, particularly when using integrative indicators such as the Soil Quality Index.

Materials & Methods

Study Area

This section is organized in the order of the experiment's steps, including the study area description, burning procedure, soil sampling, laboratory analyses, soil quality assessment, and statistical analyses.

The study was conducted in a paddy field in Sangar district, Guilan Province, Iran (37°16′85″ N, 49°68′23″ E), with a slope of 1–3% and a mean elevation of 29 m, as shown in Figure 1. The area has a Mediterranean climate (Csa) with a mean annual precipitation of 1448 mm and a mean annual temperature of 17.7 °C. Soils are classified as udic and thermic according to U.S. Soil Taxonomy [31, 32], and the landscape consists of alluvial plains and lowlands [31],

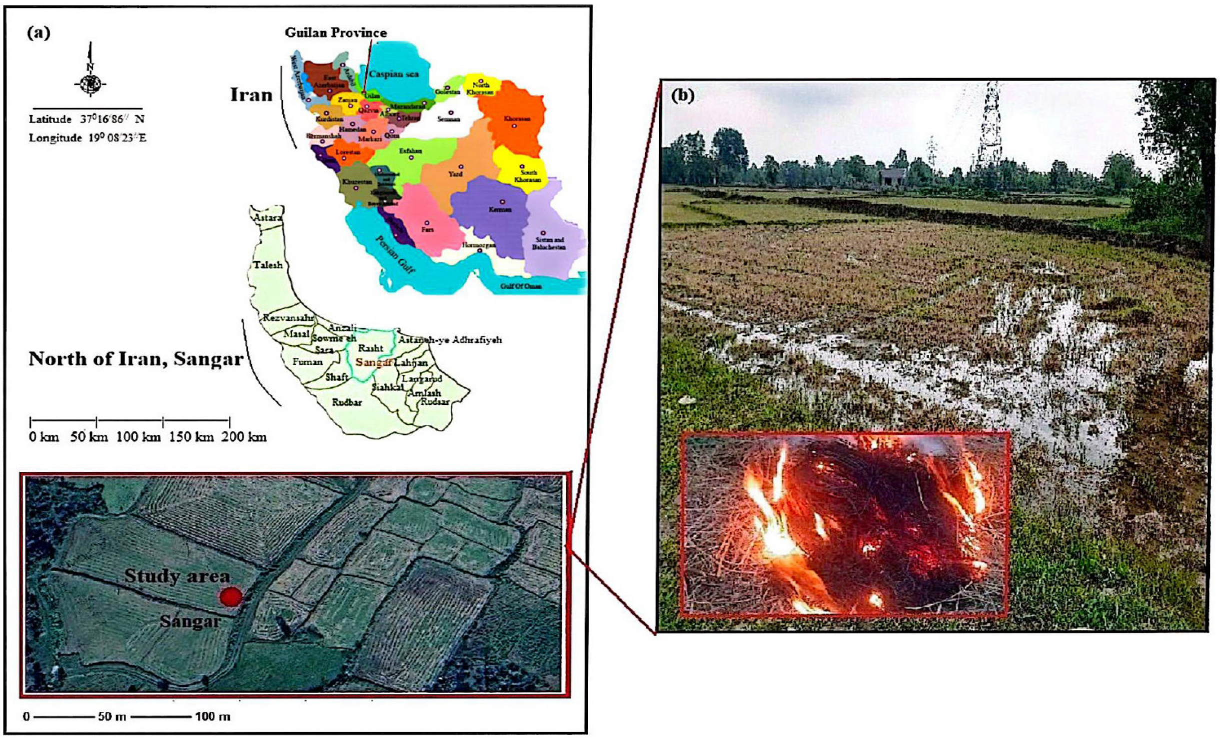

Figure 1) Study area located in Sangar, Guilan Province, Northern Iran. (a) Map showing the geographical location of the study area within Iran (b) Photograph of a typical paddy field illustrating post-harvest rice straw burning, which is widely practiced by local farmers and is relevant to the environmental assessment of the study.

with underlying metamorphic, volcanic, and sedimentary rocks. The *Hashemi* rice variety, common in Guilan, was cultivated, with typical protein and amylose contents of 8.91% and 21.38%, respectively [33, 34, 35]. Farmers apply standard Nitrogen, phosphorus, and Potassium fertilizers, and rice straw is usually burned 20–25 days after harvest.

Experimental Design and Burning Procedure of the Samples

In this study, 2 $t.ha^{-1}$ of rice straw was burned in September 2024, forming moderate fire patches covering approximately 2–3 m^2, with manual burning to avoid vehicle-induced soil compaction. This application rate corresponds to a mean straw density of roughly 0.2 $kg.m^{-2}$; therefore, each fire patch contained approximately 0.4–0.6 kg of rice straw. Rice straw was manually burned in 8 separate patches between 11:00 and 12:30 am, with each patch ignited for approximately 2 minutes. Fires reached high intensities, with flame temperatures exceeding 1000 °C and flame lengths of 1.5–3 m. [36, 37, 38]. The applied straw load and fire intensity are representative of common post-harvest residue-burning practices among local farmers in northern Iran, where straw is typically burned manually to facilitate rapid field preparation.

Soil Sampling Strategy and Laboratory Analyses

To investigate the impact of burning, soil samples were collected at two time points: immediately before the burn and shortly after. The burned area ranged from 2 to 3 m^2, and the resulting ash was included in the samples analyzed. In the paddy field, soil was randomly collected from the top 0–5 cm layer [39], with eight replicates per treatment. Soil samples were collected immediately after the fire patches were extinguished, within approximately 5–10 minutes, to capture the immediate effects of burning on soil properties. The focus on the 0–5 cm soil layer was selected because previous studies have demonstrated that both the adverse effects of fire and the protective effects of straw mulching are most pronounced in the soil surface immediately after disturbance [29, 30].

A systematic sampling strategy was used, where composite samples were created by mixing soil from multiple locations within the topsoil layer of the paddy field. All samples were air-dried, passed through a 2 mm sieve, and stored under controlled conditions before laboratory analysis.

Laboratory Analyses of Soil Physico-Chemical Properties

Clay (Cl), silt (Si), and sand (Sa) contents were determined by sieving samples and the hydrometer method [40] to evaluate texture. The following physico-chemical properties were measured: organic Carbon (OC) using the Walkley-Black method [41]; soil pH and electrical conductivity (EC) were measured in a 1:1 soil: water suspension using a calibrated pH meter and conductivity meter, respectively [42]; bulk density (BD) was determined by the clod method, where soil clods were coated with paraffin and oven-dried at 105°C until constant weight [43]; soil moisture content (SM) was measured at 5 cm depth using a portable soil moisture meter [39]; and cation exchange capacity (CEC) was determined according to Chapman [44], involving ammonium acetate saturation at pH 7 and subsequent displacement with 1 M KCl.

Soil Quality Index (SQI) Calculation Using a PCA-Based Minimum Data Set

The PCA-based minimum data set approach was selected to reduce redundancy among soil variables while retaining the most sensitive indicators of short-term fire disturbance. The overall soil quality index for each studied condition (burned and unburned soils) was evaluated using the well-known Soil Quality Index (SQI) [45]. In more detail, at the beginning of the analysis, a Principal Component Analysis (PCA) was applied to the measured soil variables to choose a Minimum Data Set (MDS) of 'indicators' of soil quality. PCA was performed by standardizing the original variables (expressed in different units) and computing the correlation matrix using Pearson's method. The first components, explaining at least 75% of the original variance, were retained. The indicators were identified as highly weighted variables (i.e., those with loadings within 10% of the highest factor loading or ≥ 0.40) retained for each PC [46]. After that, these variables were converted to 'scores' using a linear transformation and ranked in ascending or descending order, depending on whether higher values indicated 'good' or 'poor' soil function. For 'more is better' variables, each indicator was divided by the highest measured value (thus, the highest measured value received a score of one). Conversely, for 'less is better', the lowest measured value was divided by each measure in the denominator (the lowest measured value thus received a score of one) [45]. After that, the scores of measured indicators at each sampling point were weighted using the PCA loadings. The eigenvalue percentage for each principal component was used as the weight for each score. At the end of the analysis, the weighted scores for each sampling point were summed, and the mean for each studied condition (burned and unburned soils) was calculated. Linear scoring functions were selected for their simplicity, transparency, and widespread use in soil quality assessments, particularly for short-term, management-induced changes. The PCA threshold values were chosen to retain the majority of the system's variance while minimizing redundancy among indicators.

Statistical Analyses

Statistical analyses were performed to compare pre- and post-burning values, using paired t-tests to assess significant differences at the 99% confidence level after checking the data's normality. The Shapiro-Wilk and Levene tests were used to assess the assumptions of the t-test: equality of variances and normality of the data, respectively. The PCA was also used to calculate the SQI by selecting fewer soil property derivatives while retaining as much information as possible. At the end of the analyses, soil conditions were assessed using the Agglomerative Hierarchical Cluster Analysis (AHCA) [47]. The accuracy of the established model based on soil characteristics was evaluated using the coefficient of determination (R^2), the Nash and Sutcliffe efficiency (NSE), and the root mean square error (RMSE). In this study, data analysis was conducted using the Origin (Pro) software (release 2025, OriginLab Corporation, Northampton, MA, USA).

Findings

Effects of Burning on Soil Physical and Chemical Properties

All of the examined soil properties showed significant differences between the two conditions ($p < 0.01$), except for bulk density, cation exchange capacity, and soil texture components. Significant physical and chemical changes associated with soil burning are summarized in Table 1.

Table 1) Comparison of selected physical and chemical properties of unburned and burned soils in the study area.

Soil Properties	Conditions	
	Unburned Soil	Burned Soil
SM (%)	32.37 ± 1.85^a	21.62 ± 1.85^b
OC (%)	2.11 ± 0.07^a	1.41 ± 0.13^b
BD (g.cm^{-3})	1.44 ± 0.03^a	1.47 ± 0.02^a
pH (1:1)	6.97 ± 0.13^b	7.94 ± 0.06^a
EC (dS.m^{-1})	1.88 ± 0.08^b	2.94 ± 0.05^a
CEC (cmol.kg^{-1})	31.99 ± 0.54^a	33.97 ± 0.57^a
Sa (%)	27.30 ± 0.21^a	29.43± 0.10^a
Si (%)	35.00 ± 0.43^a	33.35 ± 0.21^a
Cl (%)	37.70 ± 0.22^a	37.23 ± 0.11^a
Texture	Clay Loam	Clay Loam

Notes: SM = soil moisture; OC = organic Carbon; BD = bulk density; EC= electrical conductivity; CEC = cation exchange capacity; Sa = sand; Si = silt; Cl = clay.

More specifically, SM and OC were higher in the unburned soil than in the burned soil. The latter condition showed higher pH and EC (7.94 ± 0.06 and 2.94 ± 0.05 dS.m^{-1}, compared with 6.97 ± 0.13 and 1.88 ± 0.08 dS.m^{-1} in unburned soils). Finally, BD, CEC, and the contents of sand, silt, and Clay did not differ significantly between burned and unburned soils. The relative deviation of the soil variables is presented in Table 2. Soil moisture and organic Carbon exhibited the most significant deviation values, indicating that these properties responded more strongly to the burning event and showed greater short-term variability than the more stable physical parameters.

Determining the Effects of Soil Properties

The PCA identified two principal components that accounted for 92.85% of the total variance (83.58% for PC1 and 9.27% for PC2). PC1 clearly separates burned from unburned soils, mainly due to substantial contributions from OC, SM, pH, and EC, indicating that these properties are the key drivers of post-fire differences. PC2 was primarily influenced by BD, reflecting its lower sensitivity to burning compared with the variables grouped along PC1 (Figure 2a). The AHCA clustered the soil samples in non-homogeneous groups. In this analysis, two classes of soil samples were clearly distinguished by soil properties. All samples related to burned soils were grouped into a single class (class 1). However, the samples from unburned soils fell into class 2 as presented in Figure 2b.

Table 2) The relative deviation of soil properties in the studied paddy field.

Soil Properties	Relative deviation (%)
SM (%)	21.60
OC (%)	21.43
BD ($g.cm^{-3}$)	2.13
pH (1:1)	6.84
EC ($dS.m^{-1}$)	22.98
CEC ($cmol.kg^{-1}$)	3.49
Sa (%)	3.91
Si (%)	2.67
Cl (%)	0.79

Notes: SM = soil moisture; OC = organic Carbon; BD = bulk density (BD); EC= electrical conductivity; CEC = cation exchange capacity; Sa = sand; Si = silt; Cl = clay.

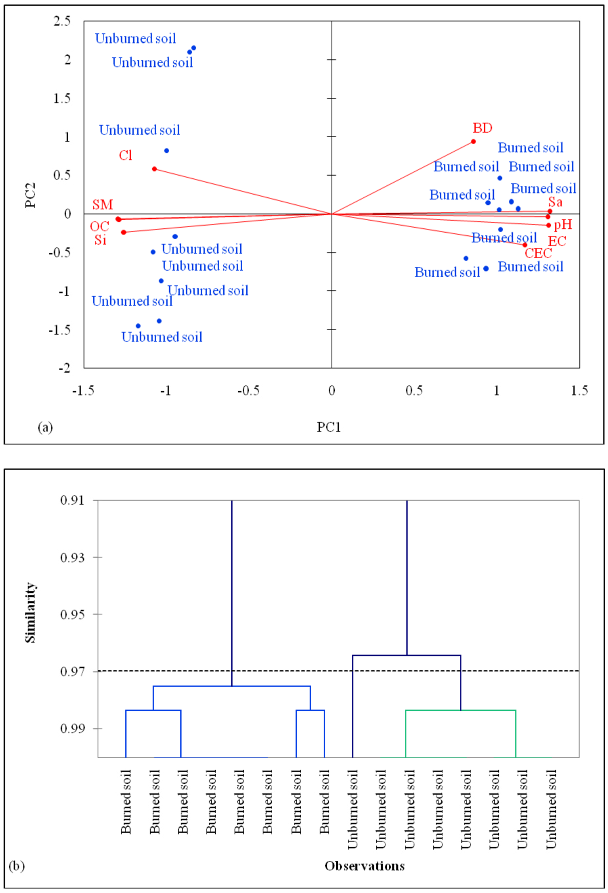

Figure 2) Results of multivariate statistical analyses applied to soil properties measured in samples collected under the studied conditions. (a) Principal Component Analysis (PCA) illustrating the relationships among soil variables along the first two principal components (PC1 and PC2). (b) Agglomerative Hierarchical Cluster Analysis (AHCA) depicts the clustering pattern of soil samples based on their physicochemical properties. SM, soil moisture; OC, organic Carbon; BD, bulk density; EC, electrical conductivity; CEC, cation exchange capacity; Sa, sand; Si, silt; Cl, clay.

Comparison of Soil Quality Index (SQI) between Burned and Unburned Soils

The SQI analysis indicated that nearly half of the soil properties significantly influenced soil quality, particularly soil moisture and organic Carbon content, as indicated by the MDS method (Figure 3). The unburned soil showed a significantly ($p < 0.001$) higher SQI (2.12 ± 1.20) compared to burned soil (1.20 ± 0.20), based on the considerable impacts of soil moisture and soil organic

Carbon on this index (both variables had a significant loading on the first PC with high loadings, 0.93 and 0.94, respectively).

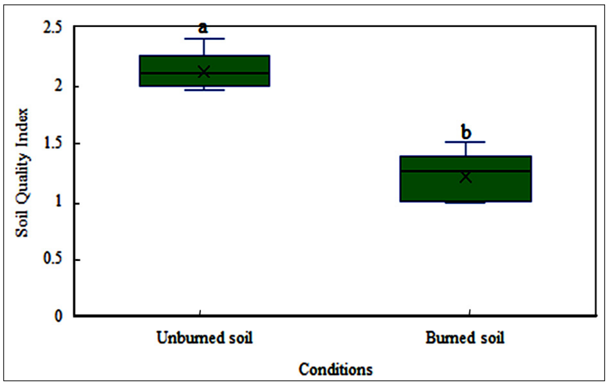

Figure 3) Distribution of the Soil Quality Index (SQI) for soils under unburned and burned conditions as illustrated by box plots. Boxes indicate the interquartile range around the median, while whiskers represent data variability. A significant difference in SQI was detected between the two soil conditions ($p < 0.01$).

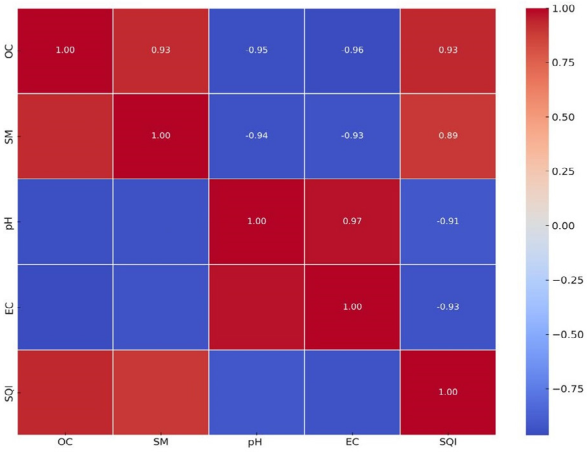

Figure 4) Pearson correlation heat map illustrating the correlations between the Soil Quality Index (SQI) and main soil properties measured in unburned and burned soils. The color scale indicates the magnitude and sign (positive or negative) of Pearson correlation coefficients. Abbreviations: SM, soil moisture; OC, organic Carbon; BD, bulk density; EC, electrical conductivity; SQI, Soil Quality Index.

Soil Quality Index Modelling Based on Soil Physico-Chemical Properties

Figure 4 presents a Pearson correlation heatmap illustrating the strength and direction of correlations between the Soil Quality Index (SQI) and key soil properties under unburned and burned conditions. The SQI showed positive correlations with organic Carbon and soil moisture, and negative correlations with soil pH and electrical conductivity ($p < 0.01$). Therefore, the mentioned soil properties were used to model the soil quality index. The suggested model for estimating soil quality index is the following:

$$SQI= +0.719\ OC+0.003\ SM-0.102\ PM-0.244\ EC+1.664 \quad \text{Eq. (1)}$$

where SQI is soil quality index, OC is organic Carbon (%), SM is soil moisture (%), and EC is electrical conductivity ($dS.m^{-1}$).

Figure 5 compares observed and predicted SQI values, demonstrating the model's predictive performance using key soil properties. The model showed strong predictive ability for the dependent variable ($R^2 = 0.88$ for the soil quality index), with predicted values very close to the 1:1 line. Moreover, the RMSE and NSE indices were within acceptable ranges for this equation, as presented in Table 3.

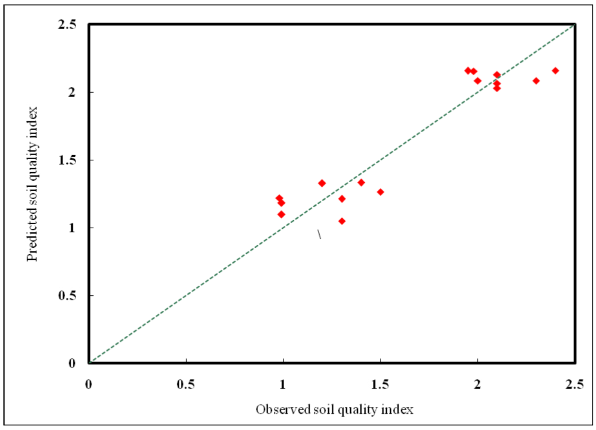

Figure 5) Comparison between observed and predicted Soil Quality Index (SQI) values obtained using a prediction model based on organic Carbon, soil moisture, pH, and electrical conductivity.

Table 3) Assessing the ability of an established model from soil properties for predicting the soil quality index.

Studied Variable		Mathematical Statistics				Accuracy Index		
		Mean	Max	Min	Std. Dev.	R^2	NSE	RMSE
SQI	Observed	1.66	2.40	0.98	0.51	0.88	0.88	0.16
	Predicted	1.65	2.16	1.05	0.45			

Note: SQI = Soil quality index and Std. Dev. = Standard Deviation.

Discussion

Effects of Burning on Soil Physical and Chemical Properties

These results confirm that dynamic soil properties are susceptible to short-term fire disturbances. Reductions in soil moisture and organic Carbon after burning likely reflect direct water loss and rapid oxidation of surface residues, while increases in pH and electrical conductivity result from ash-derived soluble alkalinity as presented in Table 1. These shifts highlight that even brief rice straw fires can markedly alter dynamic soil quality parameters, affecting fertility and water retention, consistent with observations in Mediterranean and Southeast Asian paddy soils [11, 23].

The significant reduction in soil moisture is attributable to both the direct thermal loss of water during combustion and the removal of straw mulch. In the latter case, straw mulch can act as an insulating layer, retaining moisture and reducing evaporation [48]. The destruction of surface residues exposes the soil to increased evaporative losses, compounding the moisture deficit. This mechanism aligns with a previous study that showed how fire can induce hydrophobicity and alter soil water dynamics, particularly in semi-arid regions [49]. Similar moisture reductions following biomass burning have been reported in paddy systems of Thailand [37], Mediterranean heathlands [50], and forest ecosystems [51], where fire was shown to increase soil water repellency and reduce infiltration. Furthermore, Kumar et al. [12] found that soil moisture content declined by more than 8.72% after burning, underscoring the rapid impact of combustion on soil hydrological function.

Similarly, the decline in organic Carbon content observed in burned soils can be explained by the rapid oxidation of rice straw and loose surface organic Carbon during combustion. In this study, organic Carbon decreased from 2.11 ± 0.07% in unburned soils to 1.41 ± 0.13% in burned soils, representing a reduction of approximately 33%, which confirms the sensitivity of surface and native organic Carbon to the fire event under local conditions. This results in the release of Carbon as CO_2, leaving behind mineral ash with minimal residual char. Another study has demonstrated that open-field burning of crop residues results in significant reductions in soil organic matter, thereby diminishing soil structure, aggregate stability, and nutrient cycling [52]. Organic matter serves as a critical binding agent in soil aggregation processes [53]; its loss therefore compromises both structural stability and microbial habitat, although aggregate stability was not directly measured in this study. In the present study, the substantial reduction in organic Carbon suggests that fire intensity or post-fire soil conditions (e.g., low moisture, complete combustion) were sufficient to oxidize not only surface residues but also portions of native soil organic Carbon. This contrasts with findings by Arunrat et al. [39], who reported no significant change in soil organic Carbon content immediately after straw burning in Thailand, likely due to lower fire severity or soil moisture buffering. Thus, our results emphasize the sensitivity of soil organic Carbon pools to local fire conditions and residue loads. The immediate decline in soil moisture and organic Carbon following rice straw burning highlights the vulnerability of exposed soil surfaces after residue removal. Previous studies have shown that maintaining surface residues, such as straw mulch, can help preserve soil moisture and organic matter by providing protective cover and reducing evaporation .The application of straw reduced sediment concentration in runoff from 9.8 to 3.0 g $.L^{-1}$, sediment yield from 70.34 to 15.62 g, and soil erosion rate from 2.81 to 0.63 $Mg.ha^{-1}. h^{-1}$ [29, 30]. These observations underscore the importance of adopting alternative residue-management practices in paddy fields to mitigate short-term soil degradation caused by residue burning.

Unlike the soil properties mentioned above, pH and EC increased significantly in burned soils, primarily due to ash deposition. Ash from rice straw burning is rich in alkaline elements, including Calcium, Potassium, and Magnesium. The increase in soil pH is due to the presence of alkaline and alkaline-earth elements (Ca^{2+}, Mg^{2+}, K^+, Na^+) in the soil solution. This is a well-documented outcome of fire-induced alkalinization [39, 50, 54]. Our results revealed a significant shift toward alkalinity in burned soils, consistent with other reports of post-fire pH increases, such as a pH rise from 6.2 to 7.5 following experimental burning in Mediterranean heathlands [12, 50]. Elevated EC in burned soils further supports this mechanism, reflecting an accumulation of soluble salts derived from ash inputs. Rice straw ash contains abundant Potassium, Carbonates, and other soluble ions that contribute to short-term salinization, as observed in similar residue-burning studies [55].

Despite these substantial changes, no statistically significant differences were detected in bulk density, cation exchange capacity, and soil texture. This shows that the fire intensity was insufficient to alter these more stable properties, or that the short time between burning and sampling did not allow sufficient time for detectable changes to manifest. Data from the present research showed that bulk density did not change significantly after burning, with values of 1.44 ± 0.03 $g{\cdot}cm^{-3}$ in unburned soils and 1.47 ± 0.02 $g \cdot cm^{-3}$ in burned soils (Table 1). This indicates that the fire intensity and short duration were insufficient to alter this relatively stable physical property, despite the observed reductions in organic Carbon and soil moisture. Changes in bulk density are likely limited to the immediate surface layer and may also depend on post-fire soil conditions, soil type, and mechanical disturbances such as tractor operations [19, 56].

Soil texture remained stable (clay Loam), and CEC showed no significant change (31.99 ± 0.54 vs. 33.97 ± 0.57 $cmol.kg^{-1}$), indicating that inherent soil properties are resilient to short-term fire. Despite the decline in organic Carbon, residual organic matter and Clay maintained sufficient adsorption capacity, consistent with the findings of Fonseca et al. [57].

Determining the Effects of Soil Properties

To elucidate how fire influences key soil properties and their interactions, multivariate analyses were applied to integrate the combined effects of soil moisture, organic Carbon, and other physicochemical parameters across treatments. Principal Component Analysis (PCA) revealed that soil moisture and organic Carbon were the dominant contributors to the observed variance, as shown in Figure 2a. highlighting their central role in differentiating burned and unburned soils. The first principal component clearly separated burned from unburned treatments, indicating that these key properties shift systematically following fire disturbance. Agglomerative Hierarchical Cluster Analysis (AHCA) further supported this pattern by grouping soil samples into two distinct clusters corresponding to burned and unburned conditions.

Similar multivariate responses of soil properties to fire have been widely reported in previous studies. Fire-induced combustion and thermal alteration of organic matter commonly result in significant reductions in soil organic Carbon, which, in turn, affect soil structure, aggregation, and water retention capacity [11]. Moreover, comprehensive reviews have shown that soil organic Carbon and moisture are frequently key drivers of post-fire variability across different ecosystems and fire intensities [58]. These findings are consistent with our results, indicating that moderate-intensity rice straw burning rapidly alters fundamental soil physicochemical relationships.

Overall, the observed multivariate patterns suggest that fire induces a rapid reorganization of soil properties by depleting organic Carbon and modifying soil moisture dynamics. The application of PCA and AHCA provides a robust analytical framework for identifying these integrative shifts and linking short-term fire effects to well-established soil ecological processes.

Comparison of Soil Quality Index (SQI) Between Burned and Unburned Soils

The observed reduction in the Soil Quality Index in burned soils highlights how residue removal disrupts the soil's protective mechanisms and overall functionality, as presented in Figure 3 .This emphasizes the importance of immediate residue management strategies to maintain soil resilience under fire-affected conditions. Soil Quality Index provided an integrated measure of these changes and confirmed a substantial reduction in overall soil health following rice straw burning. The 43% decrease in SQI was driven primarily by reductions in soil moisture and organic Carbon contents, reaffirming the importance of these parameters in maintaining soil function and ecosystem services. This is consistent with other studies showing that SQI is sensitive to management-induced losses of organic inputs and water retention capacity [59, 60].

Taken together, the findings of this study demonstrate that even a single short-duration rice straw-burning event can significantly affect critical soil quality variables, such as organic Carbon and soil moisture, leading to measurable degradation of overall soil quality. The lack of significant changes in cation exchange capacity, bulk density, and texture further suggests that the immediate impacts of fire are more pronounced on dynamic rather than inherent soil properties. This emphasizes the vulnerability of agroecosystems in northern Iran to the adverse effects of biomass burning. Additionally, soil quality is influenced by vegetation composition and stand structure, underscoring the importance of assessing short-term disturbances, such as rice straw burning, in northern Iran [61]. Root characteristics and soil properties, such as increased root diameter, organic matter, and plasticity, have also been shown to reduce soil detachment and erosion risk, serving as reliable indicators of soil resilience to disturbances [62]. Given that organic Carbon and moisture play fundamental roles in supporting soil biological activity, structural integrity, and nutrient retention [63, 64, 65], their depletion poses long-term risks to agricultural sustainability. Therefore, sustainable alternatives, such as incorporating residues into the soil, composting, or converting residues to biochar, should be prioritized to prevent irreversible declines in soil functions and to ensure the resilience of paddy systems under intensifying land-use pressures.

Soil Quality Index Modelling Based on Soil Physico-Chemical Properties

The empirical model for SQI showed that organic Carbon (OC) and soil moisture (SM) positively influenced soil quality, whereas pH and electrical conductivity (EC) negatively affected it. Specifically, OC in Eq. (1) had the highest impact (coefficient = 0.719), followed by SM (0.003), whereas pH and EC decreased SQI by 0.102 and 0.244, respectively. This highlights that variations in OC and SM are the main drivers of differences in soil quality between burned and unburned soils [66].

The proposed model concerns changes in soil properties immediately after fire, which have been observed in Mediterranean climates. The conditions under which this equation is valid include soils in paddy field systems with high organic Carbon. However, to apply the model at other scales, alternative mathematical relationships need to be tested to assess the long-term impacts of fire on paddy field systems.

Conclusion

The investigation has shown that soil properties can be modified by fire in paddy fields in Iran's northern Guilan Province. Although the soil textures of the studied soils were similar, organic Carbon and soil moisture were significantly different before and after fire, as we hypothesized. Soil organic Carbon and soil moisture were positively correlated with soil quality. Conversely, soil pH and electrical conductivity were negatively correlated with soil quality. The observed changes in key soil properties confirm our hypothesis: organic Carbon and soil moisture decreased by approximately 33% and 34%, while pH and electrical conductivity increased by 13% and 56%, respectively, following rice straw burning. These alterations led to a measurable decline in the Soil Quality Index, indicating a significant reduction in soil quality. Therefore, the research hypothesis is accepted, and the established SQI model, based on these four properties, reliably reflects the impact of burning on paddy soils. Rice straw burning markedly affects the topsoil of paddy fields, causing reductions in organic Carbon and soil moisture, along with increases in pH and electrical conductivity. These changes collectively lead to a significant decline in the Soil Quality Index, demonstrating the sensitivity of dynamic soil properties to fire. To mitigate these adverse effects and maintain soil health, several practical measures are recommended: incorporating rice residues into the soil rather than burning them; applying compost or biochar to replenish organic matter; maintaining optimal moisture levels during the cropping season; and minimizing mechanical disturbances, such as repeated tractor traffic. Adoption of these strategies can enhance soil resilience and support sustainable management of paddy fields. These findings provide clear evidence that burning rice straw immediately impairs soil quality, highlighting the need for alternative residue management practices, such as straw mulching, to sustain soil health in paddy fields. It should be noted that the present findings primarily reflect immediate post-fire effects and may differ from medium- or long-term soil responses. Future research should focus on long-term soil recovery, repeated burning cycles, and the integration of biological indicators to better inform sustainable residue management strategies in paddy systems. Adoption of these strategies can enhance soil resilience and support sustainable management of paddy fields. These findings highlight the vulnerability of paddy topsoil to short-term fire disturbance and support the urgent adoption of alternative residue management practices.

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References

1. Hashim N., Mohd Ali M., Mahadi M.R., Abdullah A.F., Wayayok A., Kassim M.S.M., Jamaluddin A. Smart farming for sustainable rice production: An insight into application, challenge, and future prospect. Rice Sci. 2024; 31(1): 47–61.
2. Mohidem N.A., Hashim N., Shamsudin R., Che Man H. Rice for food security: Revisiting its production, diversity, rice milling process, and nutrient content. Agriculture. 2022; 12(6): 741.
3. Chen X., Shen R., Pan B., Peng Q., Zhang X., Fu Y., Yuan W. A high-resolution distribution dataset of paddy rice in India based on satellite data. Remote Sens- Basel. 2024; 16(17): 3180.
4. Li S., Lu Z., Zhao J., Luo M., Chen F., Chu Q. Changes in planting methods will change the potential distribution of rice in South China under climate warming. Agr. Forest Meteorol. 2023; 331:(1): 109355.
5. Food and Agriculture Organization (FAO). All about rice. 2024.
6. Mahdavi S.M., Mohammadian M., Mahdavi Mashaki K., Abadian H., Nabipour A., Erfani Moghaddam R. The effect of climate changes on soil fertility and temperature stress in rice cultivation. Int. J. Plant Prod. 2025; 19(1): 167–182.
7. Limmer M.A., Linam F.A., Seyfferth A.L. The effect of rice residue management on rice paddy Si, Fe, As, and methane biogeochemistry. Sci. Total Environ. 2023; 903(1): 166496.
8. Singh L., Brar B.S. A review on rice straw management strategies. Nat. Env. Poll. Tech. 2021;20(4):1485–1493.
9. Kamboj A., Sadh P.K., Chawla P., Saharan B.S., Seth C.S., Sridhar K., Duhan J.S., Sharma M. Sustainable management of rice by-products: Environmental challenges, industrial applications, and circular bio-economy innovations. Biocatal. Agri. Biotechnol. 2024; 62: 103430.
10. Tung N.S., Cu N.X., Hai N.X. Impact of rice straw burning methods on soil temperature and microorganism distribution in the paddy soil ecosystems. ARPN J. Agri. Biologic. Sci. 2014; 9 (5): 157–160.
11. Certini G. Effects of fire on properties of forest soils: A review. Oecologia. 2005; 143(1): 1–10.
12. Kumar A., Kushwaha K.K., Singh S., Shivay Y.S., Meena M.C., Nain L. Effect of paddy straw burning on soil microbial dynamics in sandy loam soil of Indo-Gangetic plains. Environ. Technol. Innov. 2019; 16(1): 100469.
13. Tripathi S., Singh R.N., Sharma S.K. Quantification and characterization of soil physico-chemical properties influenced by wheat (*Triticum aestivum*) residue burning in India. J. Global Ecol. Environ. 2015; 2(3): 155–160.

14. Ademe Y.A. Long-term impacts of cultivation and residue burning practices on soil Carbon and Nitrogen contents in Cambisols of Southwestern Ethiopia. Am. J. Agric. For 2015; 3(3):65–72.
15. Wang G., Zhu T., Zhou J., Yu Y., Petropoulos E., Müller C. Slash-and-burn in karst regions lowers soil gross Nitrogen (N) transformation rates and N-turnover. Geoderma 2022; 425(1):116084.
16. Pradhan P., Sinha A.K., Pandit T.K. The effect of stubble burning and residue management on soil properties: A review. Int. J. Plant Soil Sci. 2024; 36(6):36–49.
17. Arunrat N., Sereenonchai S., Hatano R. Effects of fire on soil organic Carbon, soil total Nitrogen, and soil properties under rotational shifting cultivation in northern Thailand. J. Environ. Manage. 2022; 302(1):113978.
18. Arunrat N., Kongsurakan P., Solomon L.W., Sereenonchai S. Fire impacts on soil properties and implications for sustainability in rotational shifting cultivation: A review Agriculture-London. 2024; 14(9):1660.
19. Parhizkar M., Lucas-Borja M.E., Zema D.A. Effects of repeated low-severity fires on particle detachment capacity and soil properties in rills of semi-arid forests. Land Degrad. Dev. 2025; 36(11):3698-3714.
20. Thomaz E.L., Antoneli V., Doerr S.H. Effects of fire on the physicochemical properties of soil in a slash-and-burn agriculture. Catena 2014; 122(1):209–215.
21. Zema D.A., Parhizkar M., Plaza-Alvarez P.A., Xu X., Lucas-Borja M.E. Using random forest and multiple-regression models to predict changes in surface runoff and soil erosion after prescribed fire. Model. Earth Syst. Environ. 2024; 10(1):1215–1228.
22. Cheng Y., Luo P., Yang H., Li L., Luo C., Jia H., Huang Y. Fire effects on soil Carbon cycling pools in forest ecosystems: A global meta-analysis. Sci. Total Environ. 2023; 895: 165001.
23. Baur M.J., Friend A.D., Pellegrini A.F.A. Widespread and systematic effects of fire on plant–soil water relations. Nat. Geosci. 2024; 17(11): 1115–1120.
24. Kooch Y., Nouraei A., Wu D., Francaviglia R., Frouz J. The effect of fire disturbance on the dynamics of soil physical, chemical, and biological properties over time in a semi-arid region. Appl. Soil. Ecol. 2024; 202(17):105568.
25. Fox D.M., Darboux F., Carrega P. Effects of fire-induced water repellency on soil aggregate stability, splash erosion, and saturated hydraulic conductivity for different size fractions. Hydrol. Process. 2007;21(17):2377–2384.
26. Mohammadi Galangash M., Ghasemi Zolpirani R., Askari Tappeh R.F., Forouhar Vajargah M. A review on the effects of rice straw burning on the rice paddy fields, Guilan Province, Iran. Austin Environ. Sci. 2022; 7(1):1068.
27. Yıldırım A. The stubble burning problem in sustainable agriculture. Int. J. Innov. Eng. Appl. 2023;7(1):1–6.
28. Abdurrahman M.I., Chaki S., Saini G. Stubble burning: Effects on health & environment, regulations and management practices. Environ. Adv. 2020; 2(1):100011.
29. Prosdocimi M., Jordan A., Tarolli P., Keesstra S., Novara A., Cerda A. The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci. Total Environ. 2015; 547(1):302–312.
30. Prosdocimi M., Tarolli P., Cerdà A. Mulching practices for reducing soil water erosion: A review. Earth-Sci. Review. 2016; 161 (1):191 203.
31. Moloudi A., Yaghmaeian Mahabadi N. Quantitative and qualitative land suitability assessment for rice cultivation, north of Iran. Pol. J. Soil Sci. 2019; 52(2):195.
32. Soil Survey Staff. Keys Soil Taxon.. 12th ed. Washington, D.C.: NRCS, USDA; 2014.
33. Kottek M., Grieser J., Beck C., Rudolf B., Rubel F. World map of the Köppen-Geiger climate classification updated. Meteorol. Z. 2006; 15(1):259–263.
34. Rahmani N., Mani-Varnosfaderani A. Quality control, classification, and authentication of Iranian rice varieties using FT-IR spectroscopy and sparse chemometric methods. J. Food Compos. Anal. 2022; 112(1):104650.
35. Feizollahi E., Mirmoghtadaie L., Mohammadifar M.A., Jazaeri S., Hadaegh H. Effect of characteristics of four Iranian rice varieties with different agricultural districts on quality characteristics of industrial gluten-free bread. Iran. J. Nutr. Sci. Food Technol. 2018; 13(1):115–124.
36. Parhizkar M., Shabanpour M., Zema D.A., Lucas-Borja M.E. Rill erosion and soil quality in forest and deforested ecosystems with different morphological characteristics. Resources 2020; 9(11):129.
37. Navidi M., Lucas-Borja M.E., Plaza-Álvarez P.A., Carra B.G., Parhizkar M., Zema D.A. Mid-term changes in soil properties after wildfire, straw mulching and salvage logging in *Pinus halepensis* Mill. Forests 2022; 5(5):158.
38. Ryan K.C. Dynamic interactions between forest structure and fire behavior in boreal ecosystems. Silva Fenn. 2002; 36(1):13–39.
39. Arunrat N., Sereenonchai S., Sansupa C., Kongsurakan P., Hatano R. Effect of rice straw and stubble burning on soil physicochemical properties and bacterial communities in Central Thailand. Biology 2023;12(4):501.
40. Gee G.W., Bauder J.W. Particle-size analysis. In: Klute A. (Ed.), Methods of Soil Analysis, Part 1.

Physical and Mineralogical Methods. ASA-SSSA, Madison, WI; 1986:383–411.
41. Walkley A., Black I.A. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci. 1934; 37 (1):29–38.
42. Hesse P.R. Textb. Soil Chem. Anal. London: John Nurray Williams Clowes and Sons Ltd.; 1971:324.
43. Radcliffe D.E., Simunek J. Soil Phys. Hydrus: Modeling and applications. CRC Press; 201816(24):3653.
44. Chapman H.D. Cation exchange capacity. In: Black C.A. (Ed.), Methods of Soil Analysis. Am. Soc. Agron. 1965:891–901.
45. Andrews S.S., Karlen D.L., Mitchell J.P. A comparison of soil quality indexing methods for vegetable production systems in Northern California. Agr. Ecosyst. Environ. 2002; 90(1):25–45.
46. Wander M.M., Bollero G.A. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 1999; 63(4):961–971.
47. Lucas-Borja M.E., Parhizkar M., Zema D.A. Short-term changes in erosion dynamics and quality of soils affected by a wildfire and mulched with straw in a Mediterranean forest. Soil Syst. 2021; 5(3):40.
48. Ozlu E., Arriaga F.J., Bilen S., Gozukara G., Babur E. Carbon footprint management by agricultural practices. Biology 2022; 11(10):1453.
49. Lucas-Borja M.E., Zema D.A. Short-term effects of post-fire mulching with straw or wood chips on soil properties of semi-arid forests. J. Forest Res. 2023; 34(4):1777–1790.
50. Granged A.J., Zavala L.M., Jordan A., Barcenas-Moreno G. Post-fire evolution of soil properties and vegetation cover in a Mediterranean heathland after experimental burning: A 3-year study. Geoderma 2011; 164(1-2):85–94.
51. Jhariya M.K., Singh L. Effect of fire severity on soil properties in a seasonally dry forest ecosystem of Central India. Int. J. Environ. Sci. Te. 2021; 18 (12):3967–3978.
52. Halder M., Ahmad S.J., Rahman T., Joardar J.C., Siddique M.A.B., Islam M.S., Islam M.U., Liu S., Rabbi S., Peng X. Effects of straw incorporation and straw-burning on aggregate stability and soil organic Carbon in a Clay soil of Bangladesh. Geoderma Reg. 2023; 32: e00620.
53. Six J., Paustian K. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biol. Biochem. 2014; 68: A4–A9.
54. Ribeiro Filho A.A., Adams C., Manfredini S., Aguilar R., Neves W.A. Dynamics of soil chemical properties in shifting cultivation systems in the tropics: A meta-analysis. Soil Use Manage. 2015; 31(4): 474–482.
55. Abebe Nigussie A.N., Kissi E.K. Impact of biomass burning on physicochemical properties of nitisol in the southwestern Ethiopia. Afr. J. Agric. Res. 2011; 5(4):223–233.
56. Asgari H.R., Saiedyfar Z. Effects of soil compaction on soil Carbon and Nitrogen sequestration and some physico-chemical features (Case study: North of Aq Qala). J. Arid. Reg. Manage. 2014; 2(4):1–12.
57. Fonseca F., de Figueiredo T., Nogueira C., Queiros A. Effect of prescribed fire on soil properties and soil erosion in a Mediterranean mountain area. Geoderma 2017; 307(1):172–180.
58. Pellegrini A. F. A., Ahlstrom A., Hobbie S. E., Reich P. B., Nieradzik L. P., Staver A. C., Scharenbroch B. C., Jumpponen A., Anderegg W. R. L., Randerson J. T., Jackson, R. B. Fire frequency drives decadal changes in soil Carbon and Nitrogen and ecosystem productivity. Nature 2018; 553(7687):194–198.
59. De Paul Obade, V.P., Lal, R. A standardized soil quality index for diverse field conditions. Sci. Total Environ. 2016; 541(1) 424–434.
60. Chaer G.M., Myrold D.D., Bottomley P.J. A soil quality index based on the equilibrium between soil organic matter and biochemical properties of undisturbed coniferous forest soils of the Pacific Northwest. Soil. Biol. Biochem. 2009; 41(4): 822–830.
61. Rostayee F., Kooch Y., Hosseini S.M. Soil quality indices in pure and mixed forest stands of Southern Caspian region. ECOPERSIA 2015; 3(2):987–1001.
62. Sedaghatkish F., Asadi Kapourchal S., Parhizkar M. Modelling soil detachment capacity by soil properties and root diameter in soils under tree species in Northern Iran. ECOPERSIA 2025; 13(2): 137–152.
63. Xu L., Yu Q., Bai S., Wang M., Sun W., Xu S., Shi X., Lu J., Xie X., Qiu W. Soil organic Carbon impact on soil physical properties through quantity and quality modifications. Soil Adv. 2024; 2: 100014.
64. Parhizkar M., Shabanpour M., Lucas-Borja M.E., Zema D.A., Li S., Tanaka N., Cerdà A. Effects of length and application rate of rice straw mulch on surface runoff and soil loss under laboratory simulated rainfall. Int. J. Sediment Res. 2021; 36(4):468–478.
65. Pena S.B., Schaik L.V., Dorner J., Dam J.V. Dynamic soil water retention properties: Exploring the interplay of moisture states and soil structure dynamics in a compacted Andosol. Vadose. Zone. J. 2025; 24: e70021.
66. Kacergius A., Gegeckas A., Gudiukaitė R. Recent advances in soil health: Influences of organic Carbon and microbiota. Biology 2025; 14(5):500.