Trees, Forests and People 23 (2026) 101083

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

# Impact of forest fires on soil physicochemical properties in Himalayan forest ecosystems of Uttarakhand, western Himalaya

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ARTICLE INFO

*Keywords:*
Forest fire
Restoration
Management
Himalayan
Productivity
Deposition

ABSTRACT

Forest fire represents a recurrent disturbance in the Himalayan Forest ecosystems of Uttarakhand, Western Himalaya. The repeated occurrence of large-scale fire events in these forests exerts profound ecological, economic, and socio-cultural impacts. Soil is considered one of the most important natural resource and wildfire alter the nutrient status and composition of the soil. Little information is available on how soil properties such as moisture and pH level, carbon, nitrogen, phosphorus and potassium stock vary along depth-wise before and after fire. In order to address this research problem, soil samples were collected from 0–15 cm and 15–30 cm depths before and after forest fires from mixed, sal, and chir-pine forests of Uttarakhand, India. Principal Component Analysis (PCA) was used to explore the relationship among these different parameters. Before the fire, soil moisture content and organic carbon was highest in mixed forest followed by sal and chir-pine forest and after the fire, both moisture and organic carbon reduced across all forest types. Soil pH was initially slightly acidic in all forest type and after the fire pH of all forest type increased. Nitrogen and Phosphorus content was highest in mixed forest followed by chir-pine and sal forest but after fire, both the nutrients decreased. Potassium content increased after the fire due to ash deposition, and an increase in soil pH and potassium suggests nutrient redistribution. Overall, present study suggested that management of forest fire is essential to mitigate these impacts and restoration efforts to safeguard soil health and maintain ecosystem productivity in the Himalayan region.

## Introduction

Forest fire is becoming a severe environmental threat due to rising temperature leading to climate change in many regions of the world, including India. This is a global concern that results unfavorable environmental conditions and a decline in biodiversity (Vishvamitera et al., 2023). Forest fire leads combustion of above ground biomass, alteration in species and soil composition causing decreased porosity, soil organic matter (SOM) and increased pH (Certini, 2005). Moreover, the impact of forest fire on pedo-ecosystem is very complex (DeBano et al., 1998). These heating effects and changes in soil qualities often causes several flora and fauna to respond differently. Factors that affect the variability of soil responses to fire include pre-burn environment, behavior and season of fire, pre and post-fire climatic variables, such as the time of year and the amount and extent of rainfall (Clark, 2001). Vegetation loss, emergence of shrubby and grassland vegetation, and soil degradation driven on by wild fire are the main topics of scientific discussion (Jhariya and Singh, 2021).

All the ecosystem functioning and services is regulated by soil, therefore it promotes the establishment and development of agro-ecosystems and natural forest stands for the benefit of humanity (Singh et al., 2020; Meena et al., 2020). Although, soil ecosystem is greatly influenced by both biotic and abiotic factors as well as by wildfire (Singh et al., 2017; Oraon et al., 2018). These modifications can result in secondary effect like soil erosion due to increased hydrophobicity, that lowers infiltration rates and increases runoff (DeBano, 2000). Two significant factors that affect the early consequences of forest fires on soil are fire intensity and duration of combustion. Forest

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https://doi.org/10.1016/j.tfp.2025.101083

Available online 6 November 2025

fire can lead to the leaching of mineral forms of nitrogen, sulphur, and phosphorus and have a major short-term impact on soil solution concentrations (Murphy et al., 2006).

Fire is an important soil health indicator because it is a mineralizing agent and is essential for nutrient conversion (Shubham et al., 2022). The organic horizon is essential for maintaining ions and the soil's ability to exchange cations (Craswell and Lefroy, 2001). Although, the loss of organic matter is one of the most immediate changes in soil after a fire and many research studies reveal that overall amount of soil nutrients decreases following a fire, but their plant-available form rises (Certini, 2005). The changes that take place during the fire are caused by surface heating and heat transmission from burning biomass (Agbeshie et al., 2022; Elakiya et al., 2023). This heating process induces variation in particle size distribution of the burned soil (Li et al., 2021). Burned soils often contain reduced total nitrogen, higher calcium, and nearly unaltered potassium, magnesium, and phosphorus as compared to unburned soils (Neff et al., 2005). Forest fires can have both direct and indirect effects on soil nutrient status (Marion et al., 1991). Therefore, it is essential to comprehend the impacts of forest fires on soil characteristics in order to lessen their consequences and efficiently manage forest ecosystems.

Fire plays a significant role in the dynamics of terrestrial ecosystems, affecting several features, activities, and mechanisms (Fadaei et al., 2022). During the past two centuries, forest fires have caused extensive degradation, leading to the loss of millions of hectares of forested landscapes worldwide (Bhatt, 2023). The long-term impacts of fire on the chemical properties of the soil causes different reactions from nutrients over time (Hussain et al., 2024). Recurrent fires runoff and nitrogen leaching from the ecosystem are two long-term consequences of fires on soil nutrient availability that can lead to decreased nutrient availability (Wuthrich et al., 2002; Miesel et al., 2012). The impact of fire on entire soil nutrient pool is still a topic of debate in fire ecology. Forest fires are prevalent in the lower Himalayan regions, exerting substantial ecological and economic pressures on this fragile ecosystem. Their incidence has been rising annually, driven by a complex interplay of natural processes and anthropogenic influences (Sharma et al., 2023; Ahmad and Saran, 2022).

Many studies have been conducted in the last few decades to comprehend and manage the impact of forest fires on nutrient dynamics and the global carbon cycle in both natural forests and plantations regions, as well as in tropical regions (Carter and Foster, 2004; Meigs et al., 2009). For effective management of the ecosystem, it is important to understand how fire affects the physico-chemical characteristics of soil in order to preserve soil fertility and health. However, information related to forest fire and its impact on soil properties and nutrient stock are limited in India. Therefore, present study compared pre and post-fire circumstances to understand the impact of forest fire on soil properties in mixed, sal, and chir-pine forests of Uttarakhand, India, focusing on soil moisture, texture, pH, organic carbon, and nutrient content. The present study is based on the hypothesis, that the soil parameters would vary depending upon the vegetation type and the depth of soil samples. This investigation will provide valuable insights for the development of sustainable forest management strategies and the planning of ecological research in fire-affected forest ecosystems of the Western Himalaya.

## Materials and methods

### *Study area*

The Uttarakhand Himalaya, a folded and faulted chain of hills with complex geology and geomorphology, exhibit micro-level variation in soil (Surya et al., 2015). The soil of the study region comprises of four orders: Alfisols, Entisols, Inceptisols, and Mollisols, which are influenced by topographic features, macro and microclimate, parent material, and vegetation (Mhalla et al., 2019). The distinct features of sal, pine and mixed forest was presented in Table 1 and according to Murthy and Pandey (1983), brown forest soil is the dominant soil type found in this region, with soil texture ranging from sandy loam to fine sand, and sand percentage decreases with increasing altitude. Soil organic carbon, total nitrogen, and phosphorus content increases significantly with altitude (Singh, 2018). However, the potassium content is higher in oak forests than sal and chir-pine forests, and soil pH ranges from moderate acidic to slightly neutral, gradually declining with increasing altitude (Kewlani et al., 2021). Soil moisture content varies from 13.47 % to 16.68 % in winters and 42 % to 57 % in the rainy season (Kharkwal and Rawat, 2010). The distribution of different sampling points in sal, pine, and mixed forests of Uttarakhand was depicted in Fig. 1.

**Table 1**
General characteristics of surveyed forests in Uttarakhand, western Himalaya.

| S. No. | Parameter (s) | Sal forest | Pine forest | Mixed forest |
|---|---|---|---|---|
| 1 | Forest location | Motichur, Haridwar | Mauna, Nainital | Dhaulchina, Almora |
| 2 | Altitude (m a. s.l) | 320 | 1109 | 1642 |
| 3 | Latitude | 29°29′ 29.912″ | 29°23′ 42.447″ | 29°27′ 56.309″ |
| 4 | Longitude | 79°32′ 21.770″ | 79°39′ 09.842″ | 79°39′ 07.832″ |
| 5 | Canopy species | *Shorea robusta* | *Pinus roxburghii* | *Quercus leucotrichophora* |
| 6 | Soil moisture (%) | 18.04±3.91 | 22.15±4.09 | 28.90±5.43 |
| 7 | WHC (%) | 49.27±2.23 | 54.54±3.22 | 62.78±4.32 |
| 8 | pH | 6.44±0.13 | 6.43±0.34 | 5.89±0.76 |
| 9 | SOC (%) | 1.22±0.034 | 2.32±0.12 | 3.42±0.23 |
| 10 | N (%) | 0.12±0.012 | 0.21±0.091 | 0.41±0.023 |
| 11 | Soil texture (%) | Loamy sand | Sandy clay | Sandy loam |
| 12 | Sampling size | 1 ha | 1 ha | 1 ha |

WHC = Water holding capacity; N = Nitrogen; SOC = Soil Organic Carbon.

The study was carried out in three dominant forest types of the Uttarakhand, western Himalaya. These forests are renowned for their exceptional biodiversity but are also susceptible to forest fires annually (Negi et al., 2018). The diversity of forest types across the landscape gives rise to varied ecosystems, each harboring a rich array of plant species. Prominent forest types in the region include sal-dominated forest found at an elevation of 200 m a.s.l, the pine forest at 1800 m a.s.l, and the mixed forest at 2000 m a.s.l.

### *Soil sampling*

Soil samples were collected from three distinct forest types at random intervals between January and February (before the fire) and again between May and June (after the fire) for two consecutive years (2019–2020). The samples were collected by stratified random sampling method from two different depths 0–15 cm (upper) and 15–30 cm (lower) from each site. A total of 60 soil samples were taken from each site before and after the fire by using ten 0.5 × 0.5 m plots, spaced 1.5 m apart. Each sample was carefully labelled after sampling, and was stored in zipper pouch and finally transported to the GBPNIHE lab in Almora. Further, samples were then allowed to air dry before being sieved through a 2 mm sieve and kept at room temperature for further physico-chemical analysis.

### *Soil analysis*

Analysis of different soil parameters was performed by using standard established protocols like dichromate oxidation method was used to measure the amount of organic carbon in the soil (Walkey and Black, 1934). A control dynamics digital pH meter and spectrophotometer was used to measure pH and total phosphorus of the soil. Total nitrogen was measured using the traditional Kjeldahl method and flame photometer

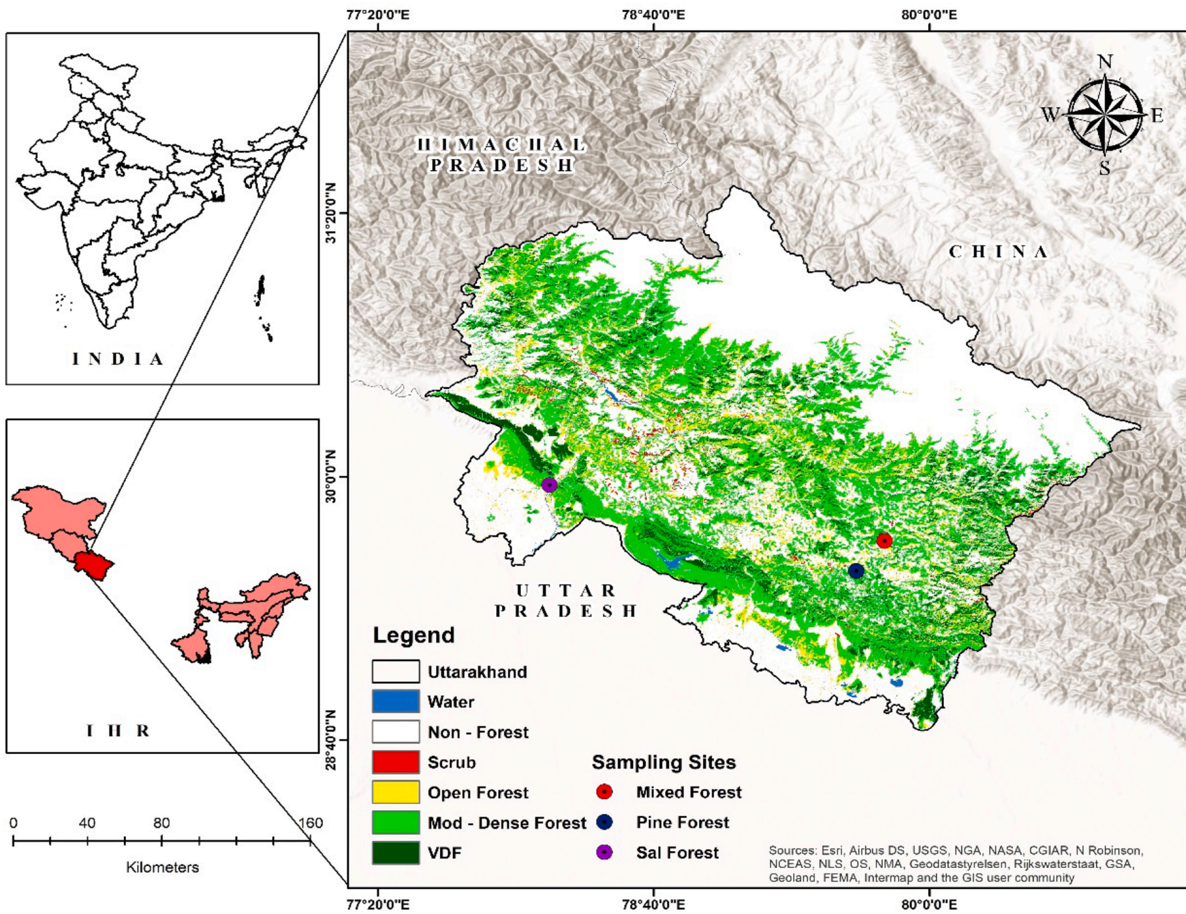


**Fig. 1.** Map showing the locations of sampling sites of 3 different forest types of Uttarakhand, western Himalaya (both pre- and post-fire).

was used to extract potassium using the neutral normal digestion method (Anderson and Ingram, 1993). Soil moisture was determined gravimetrically and soil texture was assessed through hydrometer and core sampling, respectively (Black, 1965).

*Statistical analysis*

All the physico-chemical data of the soil of two different depths were presented as mean ± *S*.E. Microsoft Excel was used for data organization, and SPSS window version 26 was used to analyze the results. Pearson's correlation coefficient was calculated at $p < 0.05$ to determine significant differences among soil properties in different fire classes. To determine the statistical significance of forest fire impacts on soil properties, an independent two-sample *t*-test was performed. The analysis compared the mean values of each soil property (e.g., pH, OC, N, P, K, SMC) from the pre-fire and post-fire sampling periods for each forest type and soil depth. All statistical analyses were performed using SPSS version 26, and significance was determined at $p < 0.05$.

## Results

*Physical parameters of soil before and after fire at 0–15 cm depth*

The severity of wildfire largely depends on moisture content and maximum soil moisture content (SMC) value observed in the mixed forest (18.39 %), followed by sal forest (12.46 %) and chir-pine forest (11.9 %) (Fig. 2a). After fire, the value of moisture content in all forest types reduces and mixed forest has highest SMC (15.69 %), followed by chir-pine (10.87 %), and sal forest (10.63 %). Soil texture varies significantly in all forest types and Chir pine forest recorded maximum proportion of sand (59.59 %) the remaining proportion of silt and clay were 26.62 % and 4.51 % respectively. However, Sal Forest recorded a lower concentration of sand (35.55 %) and the remaining silt and clay concentrations were 35.43 % and 29.42 % respectively. The soil texture of mixed forest comprises of 57.40 % sand, 28.83 % silt and 12.10 %

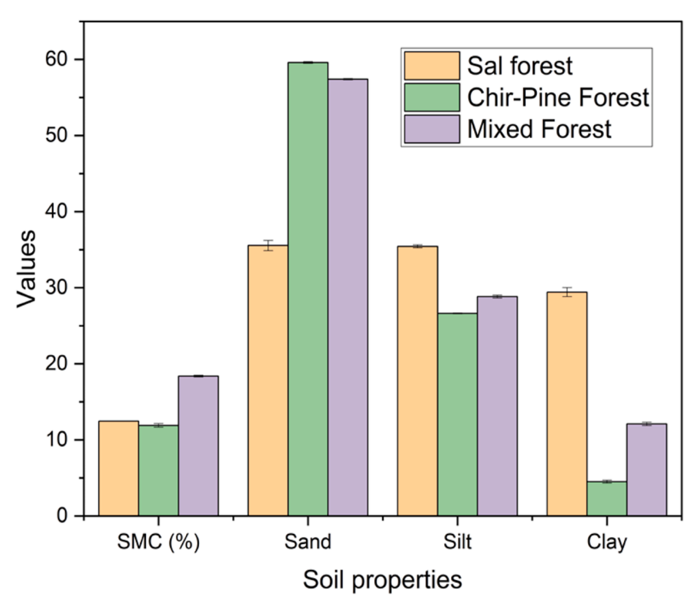


**Fig. 2a.** Physical properties before forest fire.

clay. The clay particles in all forest types reduce after the forest fire and Chir pine forest recorded highest concentration of sand (59.23 %), and the remaining silt and clay concentrations were 26.23 % and 4.38 % respectively (Fig. 2b). In Sal Forest, maximum silt (33.73 %) and clay (27.6 %) content was observed during the study. On the other hand, minimum sand concentration (31.43 %) was recorded in Sal Forest. Correlation analysis during pre-fire at 0–15 cm soil depth showed that organic carbon was positively and significantly correlated with SMC (r= 0.997), N (r= 0.984), P (r= 0.957) and K (r= 0.023) and the pH was also positively correlated with all the parameters (Fig. 3). However, the correlation matrix of soil physico-chemical parameters after fire at 0–15 cm soil depth revealed that SMC, OC and N was negatively correlated with phosphorus and potassium (Fig. 4).

*Chemical parameters of soil before and after fire at 0–15 cm depth*

The value of soil pH before forest fire was slightly acidic in all forest types with lowest pH (5.88) in Chir-Pine Forest and Sal and mixed forest recorded a pH value of 5.94 and 5.97 respectively (Fig. 5a).

Forest fires lead to deposition of nutrient-rich ash on the soil surface, resulting an increase in soil pH and mixed forest record highest pH (6.36), followed by the Sal Forest (6.35), and Chir-Pine Forest (6.10). Before forest fire, highest soil organic carbon (SOC) value was observed in Mixed Forest (2.29 %), followed by Sal (1.61 %) and Chir-Pine Forest (1.58 %). This study observed a reduction in soil organic carbon after forest fire due to sudden mineralization of organic compounds into volatile compounds. After fire, mixed forest recorded 2.01 % organic carbon followed by Chir-Pine Forest (1.37 %), and Sal Forest (1.34 %) at the surface layer (Fig. 5b). Prior to forest fire, mixed forest recorded highest N content (0.39 %) due to higher amount of litter fall, followed by Chir-Pine Forest (0.26 %) and Sal Forest (0.25 %). After forest fire, N content reduces to 0.33 %, followed by Chir-Pine Forest (0.22 %), and Sal Forest (0.21 %). Mixed Forest (0.20 %) recorded highest P value before forest fire, followed by Sal (0.13 %) and Chir-Pine Forest (0.10 %). In all forest types, the concentration of phosphorus decreases after fire due to mobility of phosphoric acid. Mixed Forest recorded (0.16 %) followed by Sal (0.10 %) and Chir-Pine Forest (0.07 %) respectively. K shows relatively high mobility in soil as it is often taken up in large amounts by tree roots and the value of K before fire was almost similar among all the three forest types (0.77 %). The concentration of K increases after the forest fire due to release of more cations in the soil. The present study recorded highest K content (1.07 %) in Sal Forest, followed by the Mixed (0.98 %), and Chir-Pine Forest (0.90 %).

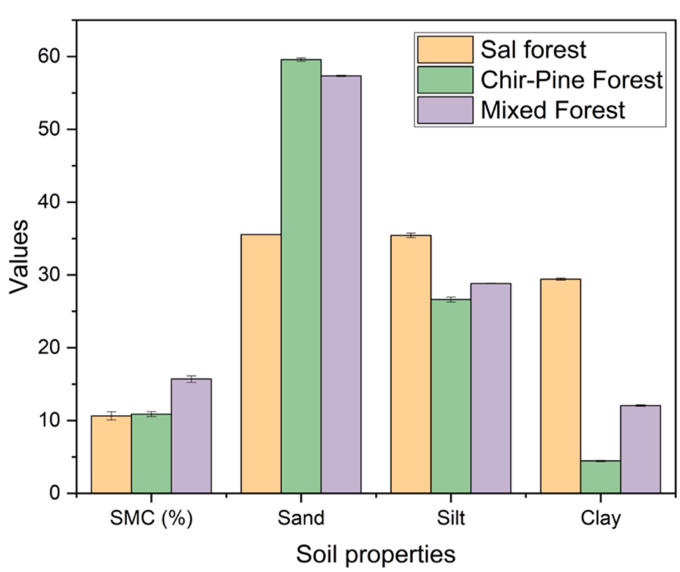


**Fig. 2b.** Physical properties after forest fire.

*Statistical significance of changes at 0–15 cm depth*

To test the significance of the observed changes, independent sample *t*-tests were performed on the 0–15 cm depth data (Fig. 6). The analysis confirms that the post-fire reduction in Soil Moisture Content (SMC) was statistically significant. This decrease was highly significant ($p < 0.01$) for all three forest types in the 2019 data and remained significant for all types in the 2019–21 aggregate data ($p < 0.05$). Conversely, the post-fire increase in Potassium (K) was also statistically significant. A significant increase was observed in Chir-Pine and Sal forests in 2019 ($p < 0.01$), in Mixed forest in 2020 ($p < 0.001$), and in Mixed and Sal forests in the 2019–21 data ($p < 0.01$). Other observed changes at the 0–15 cm depth, including the increase in pH and the decreases in Organic Carbon (OC), Nitrogen (N), and Phosphorus (P), were not found to be statistically significant ($p > 0.05$).

*Physical characteristics of soil before and after fire at 15–30 cm depth*

The SMC of all forest type increases with increase in depth and highest SMC was recorded in mixed forest (18.56 %) due to dense vegetation before forest fire, while chir- pine forest has the lowest SMC (11.54 %). High temperature caused by the fire decreases the moisture level in all forest types and mixed forest recorded 16.18 % SMC, followed by chir-pine Forest (10.60 %), and sal forest (10.36 %). The soil texture of chir pine forest comprises of 59.23 % sand, 26.23 % silt and 4.44 % clay. However, sal forest recorded lower proportion of sand (35.15 %) and higher proportion of silt (33.72 %) and sand, silt and clay proportion of mixed forest were 57.27 %, 28.71 % and 11.98 % respectively (Fig. 6a). After forest fire, the soil texture of all forest types remains the same, only a marginal decrease was observed in clay particles (Fig. 6b). The correlation analysis of soil parameters during pre-fire at 15–30 cm soil depth showed that pH was positively significant with all the parameters except nitrogen (r = -0.045). Moreover, organic carbon was highly significant with N (r = 0.950) and P (r = 0.920) and the moisture content was also positively and highly significant with pH, OC, N and P (Fig.7). However, all the parameters were positively correlated with pH and OC and SMC was strongly and positively correlated with OC (r = 0.914) and N (r = 0.927) (Fig. 8).

*Chemical characteristics of soil before and after fire at 15–30 cm depth*

The soil pH was slightly acidic in all three forest types with highest pH (6.17) in mixed forest, and lowest (5.99) in chir pine forest (Fig. 9a). After forest fire, the pH increases and sal forest recorded highest pH (6.60), followed by mixed forest (6.57), and chir-pine forest (6.21). The soil organic carbon decreases with increasing soil depth in all forest types and mixed forest has the highest OC (2.18 %) due to high accumulation of leaf litter, followed by chir-pine (1.48 %) and sal forest (1.39 %). The present study observed a reduction in soil organic carbon after forest fire due to mineralization and recorded 1.86 %, 1.26 % and 1.17 % organic carbon in mixed, chir-pine and sal forest respectively (Fig. 9b). The value of N before fire was highest in mixed forest (0.37 %), followed by chir-pine (0.24 %) and sal forest (0.23 %). After fire, the value of N decreases due to volatilization and both sal and chir-pine forest have similar values of N (0.19 %). Likewise, the value of P was maximum in mixed forest (0.18 %) and decreases with increase in depth. Sal and chir-pine forest recorded 0.11 % and 0.09 % P values before forest fire. A decreasing trend in the values of P after forest fire was observed in this study and sal, mixed and chir-pine forest recorded 0.39 %, 0.15 % and 0.06 % phosphorus respectively. Sal forest recorded lowest (0.69 %) K value while mixed and chir-pine forests have similar K (0.73 %) values before fire. The present study reported an increase in K concentration after forest fire and sal and mixed forest had similar K content of 0.86 %.

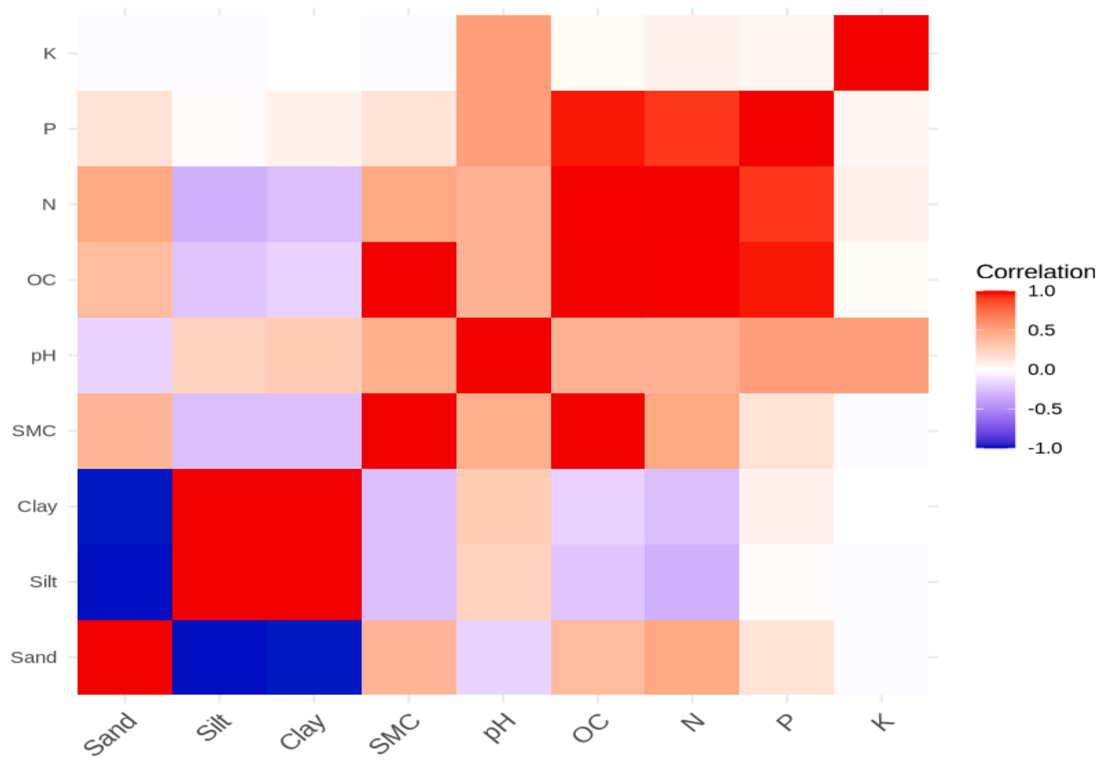


**Fig. 3.** Correlation matrix of physico-chemical attributes of soil before forest fire at 0–15 cm.

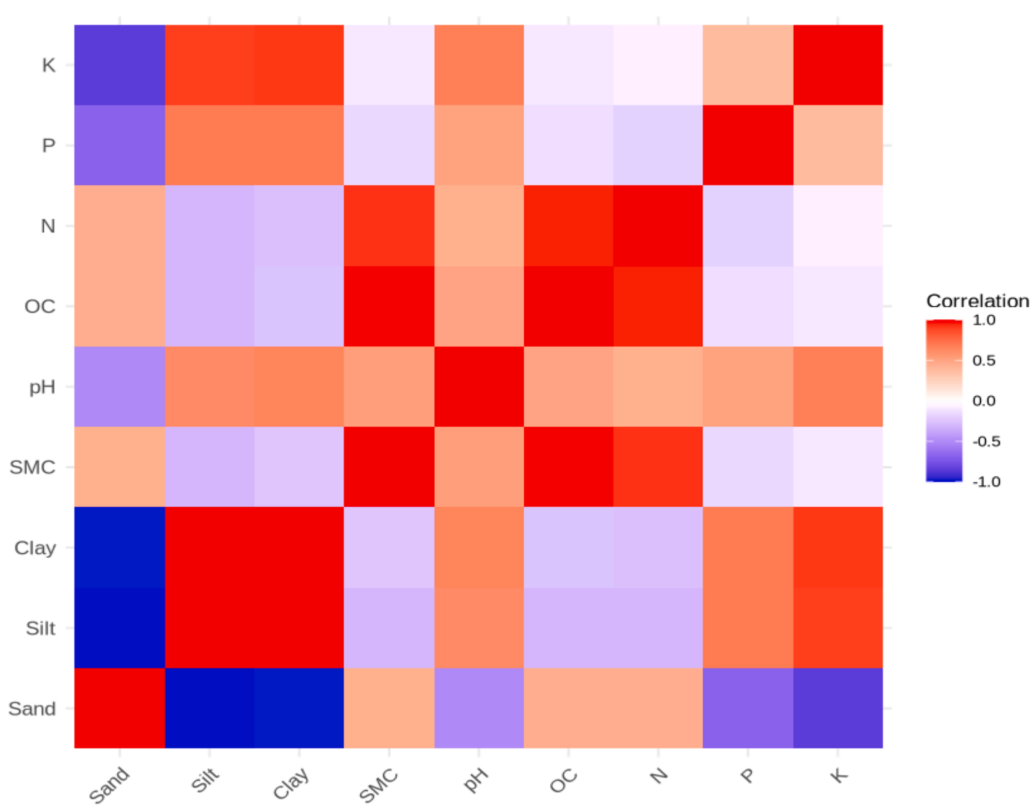


**Fig. 4.** Correlation analysis of physico-chemical properties of soil after forest fire at 0–15 cm.

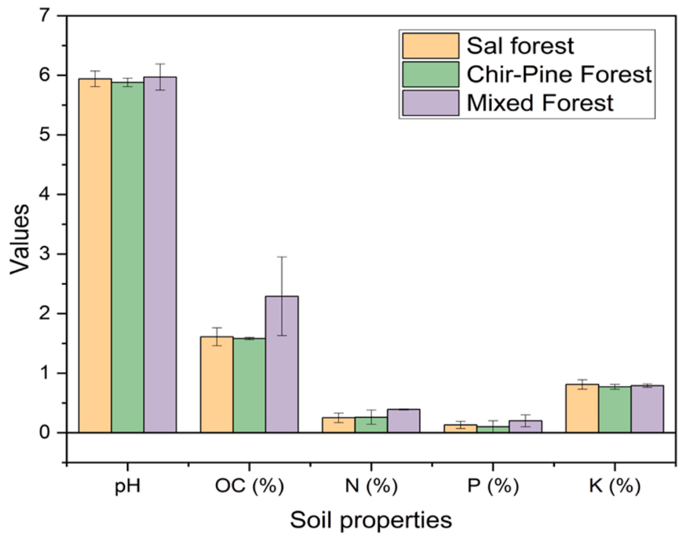


**Fig. 5a.** Chemical properties before forest fire.

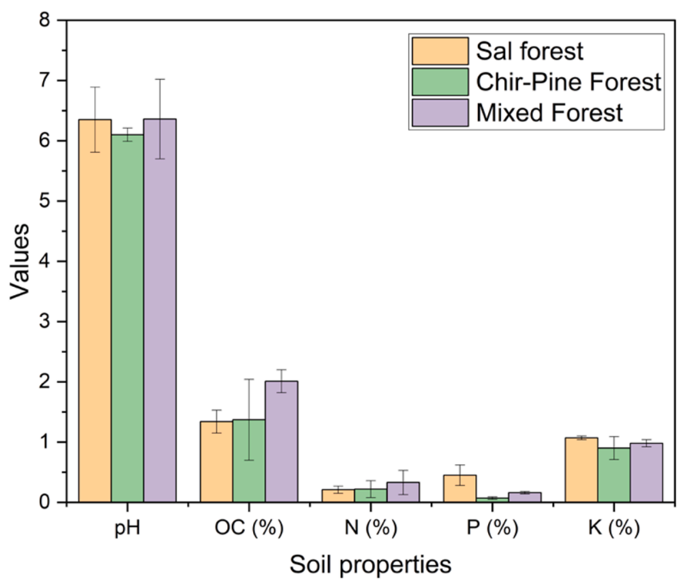


**Fig. 5b.** Chemical properties after forest fire.

*Statistical significance of changes at 15–30 cm depth*

*The t-test analysis was also applied to the 15–30 cm sub-surface layer*

Similar to the surface layer, the reduction in Soil Moisture Content (SMC) was statistically significant. This decrease was observed in the 2019 data for Sal ($p< 0.001$) and Mixed forests ($p< 0.01$), the 2020 data for Sal forest ($p< 0.001$), and the 2019–21 aggregate data for Sal ($p< 0.01$) and Mixed forests ($p< 0.05$). The post-fire increase in soil pH was also statistically significant at this depth. A significant increase was seen in the 2019 data for Sal ($p< 0.001$) and Mixed forests ($p< 0.05$), the 2020 data for Mixed forest ($p< 0.01$), and in Sal forest ($p< 0.001$) in the 2019–21 aggregate data. The reduction in Organic Carbon (OC) was significant in the 2019 data for Chir-Pine ($p< 0.001$) and Mixed forests ($p< 0.01$), but this was not consistent across other years. Other observed changes in Nitrogen (N), Phosphorus (P), and Potassium (K) at the 15–30 cm depth were not found to be statistically significant ($p> 0.05$).

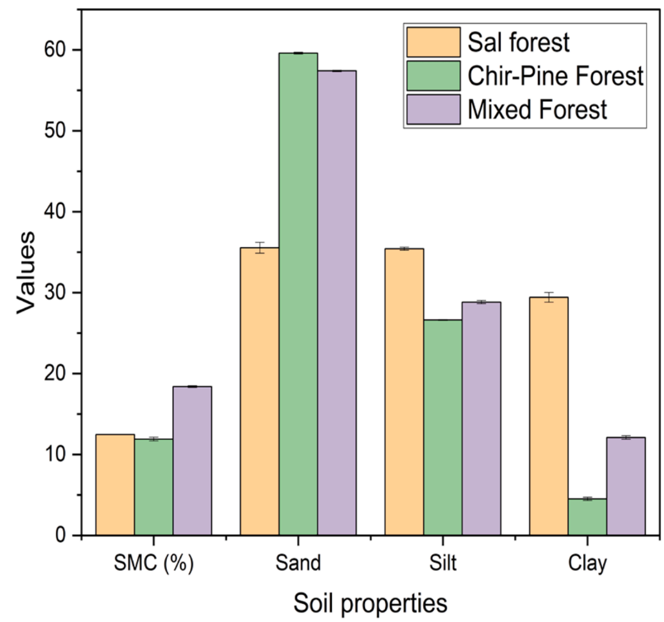


**Fig. 6a.** Status of physical properties prior to fire.

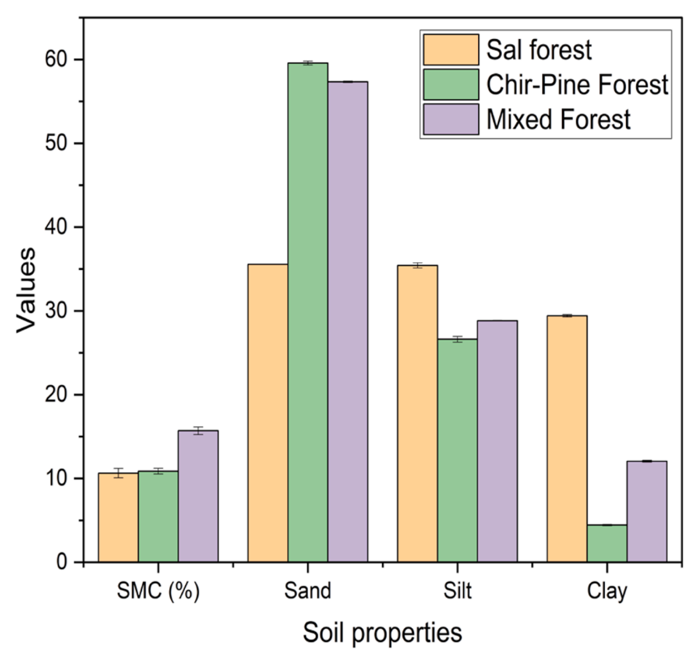


**Fig. 6b.** Status of physical properties after fire.

*Principal component analysis*

The Principal component analysis (PCA) was applied to 9 physical and chemical parameters for three different forest types to identify the most important soil factor affecting soil properties and the impact of fire. PCA resulted into two major principal components, viz. PC1 and PC2 contributed a total variance of 86.83 % and 26.66 %, respectively. The different factors, their loading values, respective eigenvalues, and total variance ( %) for each component are given in Table 2. The variance in PC1 was due to silt, clay and pH while in PC2, it was due to moisture content. However, PC1 showed strong negative loading with organic carbon, N, P and K. The biplot of PCA of 9 different variable is given in Fig. 10.

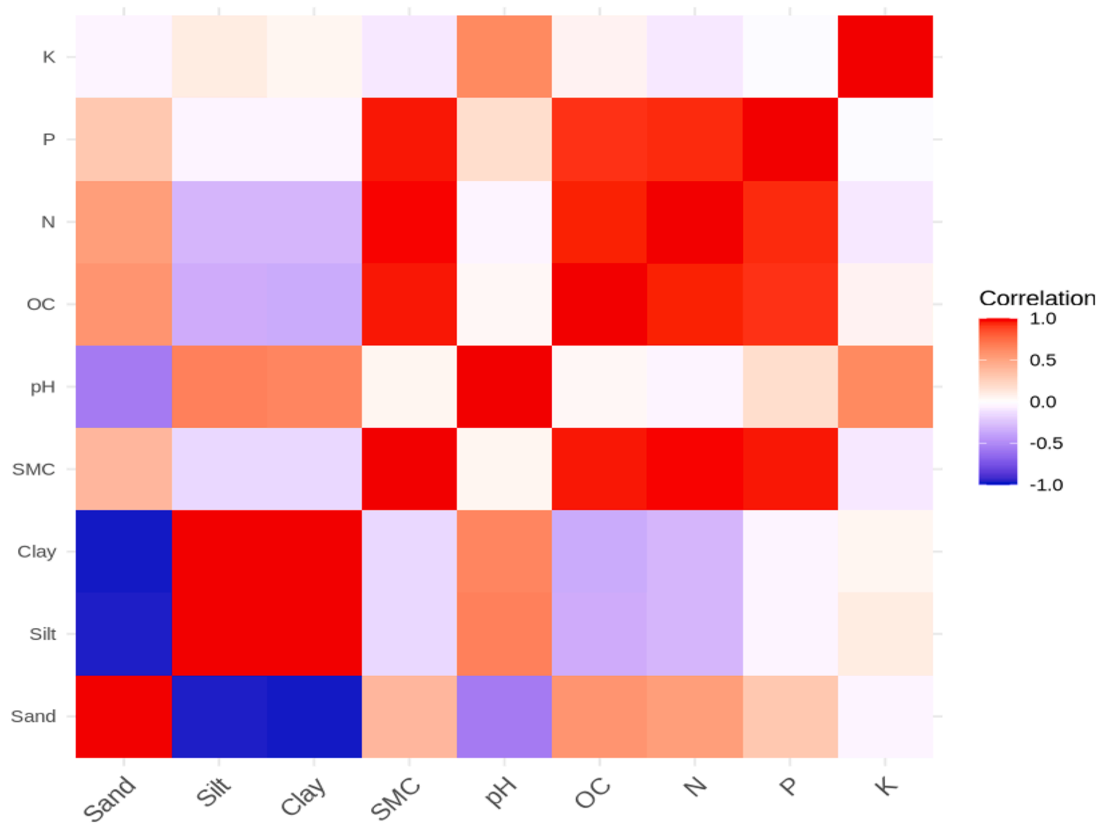


**Fig. 7.** Correlation matrix of soil physico-chemical attributes before forest fire at 15–30 cm.

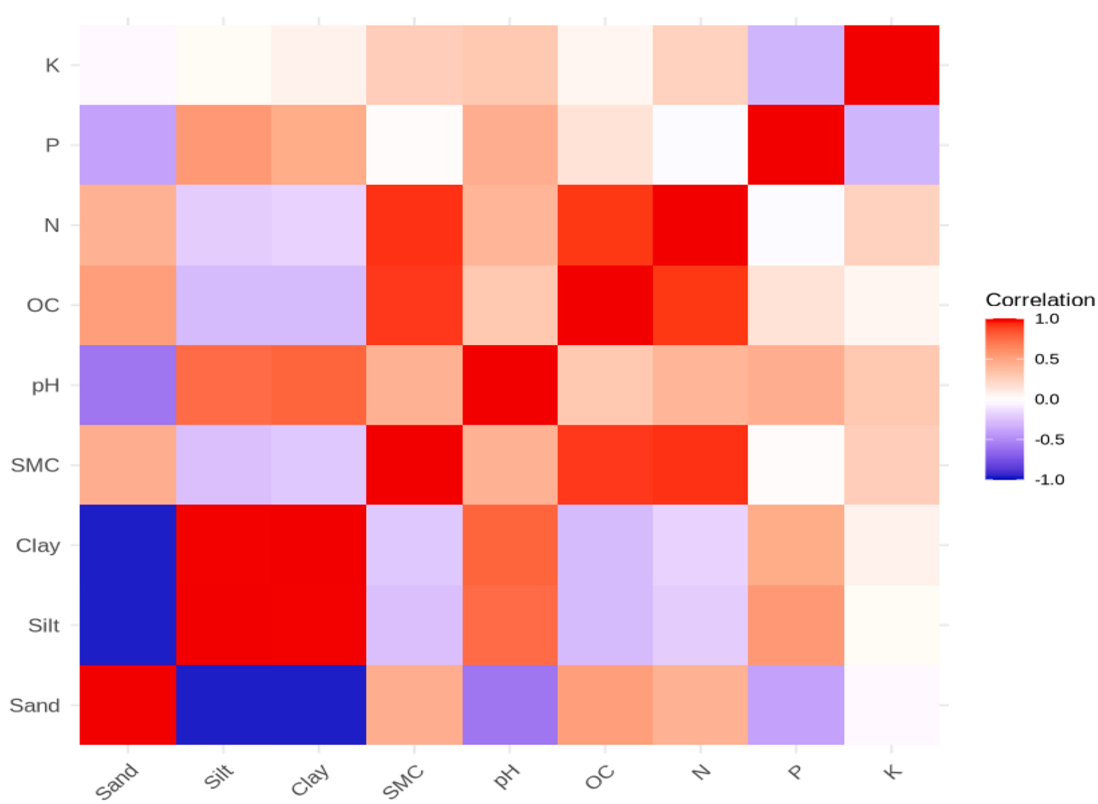


**Fig. 8.** Correlation matrix of soil physico-chemical attributes after forest fire at 15–30 cm.

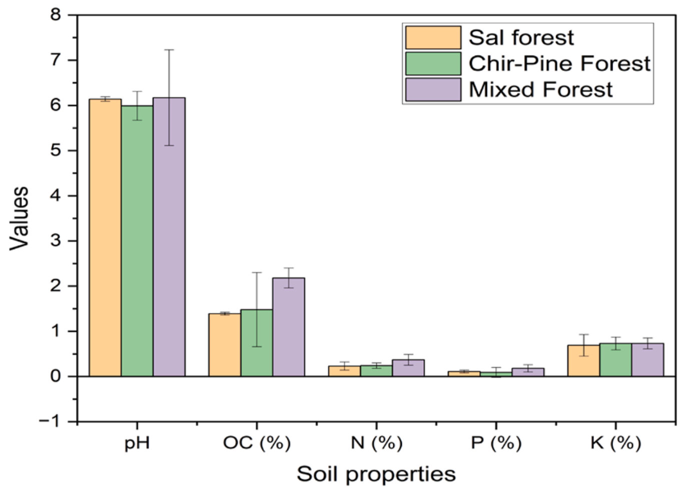


**Fig. 9a.** Status of chemical properties prior to fire.

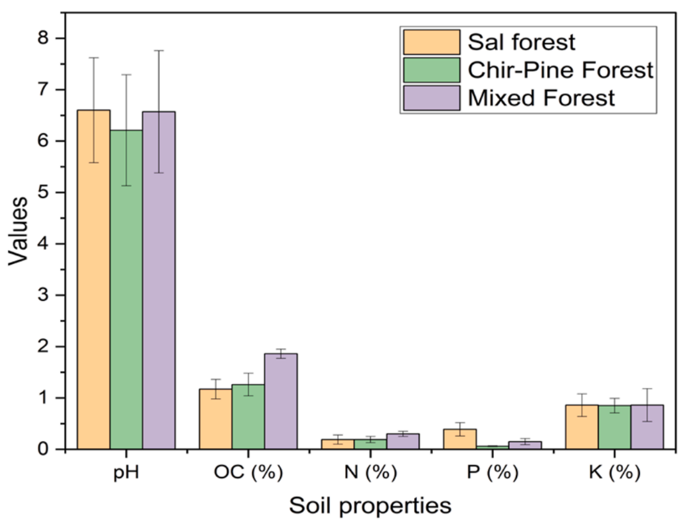


**Fig. 9b.** Status of chemical properties after fire.

**Table 2**
Principal components and Eigenvalues of physical and chemical variables.

| S. No. | Variables | PC 1 | PC 2 |
|---|---|---|---|
| 1. | Sand | -0.665 | 0.151 |
| 2. | Silt | 0.372 | 0.127 |
| 3. | Clay | 0.635 | 0.243 |
| 4. | Moisture content | -0.099 | 0.878 |
| 5. | pH | 0.018 | 0.149 |
| 6. | Organic carbon | -0.045 | 0.285 |
| 7. | N | -0.019 | 0.123 |
| 8. | P | -0.009 | 0.098 |
| 9. | K | -0.023 | 0.013 |
| 10. | Eigenvalue | 26.669 | 3.968 |
| 11. | Variance (%) | 86.836 | 12.921 |

## Discussion

Forest fire had a substantial impact on the physico-chemical characteristics of soil, thus alters the soil properties of any forest type. The extent of these alterations is directly influenced by combustion of organic matter and temperature of the soil during fire. According to the earlier studies done by (Maksimova and Abakumov, 2015; Jhariya and Singh, 2021; Li et al., 2021) the chemistry of the soil can be drastically changed by adding ash after burning biomass and organic matter completely or partially. Our study showed that there was a decline in the values of soil nutrients due to fire in the forest region, which can negatively impact the forest ecosystem by decreasing soil fertility. Similar results were observed in the forest of Garhwal and Himanchal Pradesh (Kumar et al., 2013; Mittal et al., 2019).

### *Physical characteristics of soil*

It has been reported that mixed forest has maximum amount of MC among all forest type. Earlier studies of Bargali et al., 2018 and Kashyap et al., 2020 concluded that mixed forest has maximum moisture content due to less exposure to sunlight and better quality of litter. The findings of the present study agree with this statement. Additionally, MC in chir pine forest increases with increase in depth. Similarly, Sheikh and Kumar (2010) mentioned the increment in moisture level which supports the present findings. The value of MC in sal forest ranged between 12.13–12.46 % which was found to be higher than the values reported by (Chaudhary and Joshi, 2013; Sharma et al., 2017) respectively in sal forest of Uttarakhand. Similar to our findings, reduction in moisture content in pine forest after fire has been reported by (Singh et al., 2021) in Garhwal Himalaya. It is noteworthy that the reduction in SMC observed in burnt soils could be attributed to the high temperature and soil water repellency caused by the fire (Yang et al., 2014). Similar to our findings, (Pandey et al., 2023) observed negative correlation of soil moisture content with silt content.

The results indicate that soil texture of all forest types decreased with increasing soil depth before forest fire. Pandey et al. (2023) recorded similar range of sand, silt and clay concentration in sal forest of Central Himalaya, India. The results of the present study revealed that the sand particles were slightly higher in chir pine forest than the mixed forest. Similar observation was reported by (Bargali et al., 2018) in both the forest type of Central Himalaya. After forest fire, the clay particles in all forest type reduces due to sensitivity of clay particles to high temperature. Similar observation related to soil texture was recorded in the previous study of (Ulery and Graham, 1993; Fensham et al., 2015; Alcaniz et al., 2016) that support the findings of the present study. During the present investigation, it was observed that sand particles were negatively correlated with silt and clay, which is consistent with the previous research finding of (Upreti et al., 2016).

### *Chemical characteristics of soil*

The current investigation showed that pH of mixed forest at each depth was acidic in nature and similar observations were reported by (Kumar et al., 2004; Arya, 2014) in the mixed forest of Uttarakhand. In sal forest, soil pH increased with increasing soil depth and similar results were reported by (Negi and Gusain, 2018). It was also observed that the pH of chir pine forest was slightly acidic due to high humus content. Kumar and Kumari (2019) and Bisht et al. (2023) recorded similar values of pH in chir pine forest of Kumaun Himalaya. During the present study pH was strongly correlated with macronutrients that corroborates with the observation of (Maurya et al., 2014). Forest fire significantly increases the value of pH in all forest types due to the formation of oxides, hydroxides, and carbonates of sodium and potassium. Similar to our findings, (Sharma, 2018; Singh et al., 2021) observed higher pH in burnt areas of pine and oak forest of Garhwal Himalaya. The results of the present study were in accord with the findings of (Heydari et al., 2017; Verma et al., 2019; Li et al., 2021; Vishvamitera et al., 2022) who reported the same increasing trend in soil pH due to burning of fuels and release of bases.

During the present investigation, it was observed that SOC decreased with increasing soil depth in all forest types during post-fire scenarios. The differences in OC values may be due to differences in litter quality, decomposition rates, and soil moisture. Mixed forest recorded maximum organic carbon due to high accumulation and diversity of litter in the

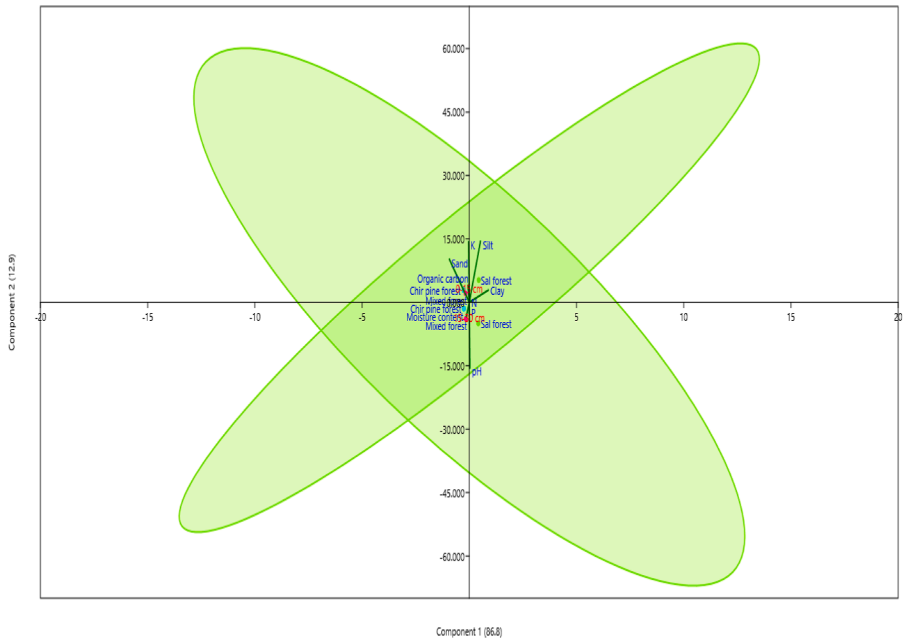


**Fig. 10.** Biplot of 9 different variables (PC1 vs PC2).

soil. These statements corroborated with the findings of (Maurya et al., 2014; Rawat et al., 2021). Our study observed a reduction in soil organic carbon (SOC) after forest fire, which is consistent with the findings of previous studies of (Chandra and Bhardwaj, 2015; Khaki et al., 2015; Verma et al., 2019; Jhariya and Singh, 2021). All of them documented lower level of SOC concentration in burnt sites over unburnt in different forest types of India. This reduction in SOC is attributed to the sudden mineralization of organic compounds into volatile compounds (Francos et al., 2018; Li et al., 2021). The findings of the present study agree with this statement. Similarly, (Kumar et al., 2013; Vishvamitera et al., 2022) reported a substantial loss of organic matter in chir pine forest of Garhwal and North western Himalaya.

The nutrient status of different forest type varies greatly and any difference in total nutrient is due to forest fire and its related processes. In present finding, the value of N was highest in mixed forest before fire due to higher amount of litter fall. Rawat et al. (2021) and Mehta et al. (2022) also recorded maximum N content in mixed forest of Western Ramganga valley and Kumaun Himalaya. In Chir pine forest, N content decreases with increase in soil depth and sal forest recorded sufficient amount of N content due to the presence of organic matter. Likewise, (Semwal et al., 2009; Joshi and Negi, 2015; Bharti et al., 2016; Pandey et al., 2023) reported similar values of N in chir pine and sal forest of central and western Himalaya. Our study observed a decrease in nitrogen content after forest fire due to volatilization, erosion, and leaching. Various scientists have reported similar declining pattern due to fire in chir pine forest of Himalayas (Kumar et al., 2013; Khaki et al., 2015; Mittal et al., 2019).

Fire incident reduces nutrient uptake and influences P pool of different forest type and in present investigation, mixed forest recorded highest concentration of phosphorus before fire. As per earlier research report of Sheikh et al. (2009); Gairola et al. (2012), mixed forest of Garhwal Himalaya constitute maximum value of P. In the present investigation, the value of P in chir pine forest ranged from 0.09–0.10 % due to greater input of organic matter. Semwal et al. (2009) and Tewari et al. (2016) reported similar values of P that support the outcomes of the present research. Forest fire lowers P concentration due to dry nature of fuel materials and higher mobility of phosphoric acid. A similar trend was reflected in the work of (Verma et al., 2019; Kumar et al., 2013; Mittal et al., 2019).

The level of K decreases with increase in depth and organic matter (Vishvamitera et al., 2022) can hold potassium by cation exchange process in all forest types. The present values of K were same in mixed and chir pine forest. Dimiri et al. (2006) and Rawat et al. (2021) also recorded maximum K in the surface layer of mixed forest of Garhwal Himalaya. Chir pine forest also showed decreasing trend of K with increase in depth. Likewise, Kumar et al. (2013) recorded similar decreasing trend of K in pine forest of Garhwal, Uttarakhand. The present study reports an increase in K concentration after forest fire in all forest types due to the release of more cations in the soil. Alexakis et al. (2021) observed similar results that supports the findings of the present research. Likewise (Mittal et al., 2019; Vishvamitera et al., 2022) reported a significant increase in K concentration in pine forest of north western Himalaya. Two principal components were identified PC1 and PC2 and Jhariya and Singh (2021) confirmed the influence of fire on soil properties with the help of PCA that validates the outcomes of the present study.

## Conclusion

Forest fires exert profound effects on soil properties in diverse forest types of the Himalayan region. The study demonstrates that forest fires lead to significant alterations in soil moisture content, texture, pH, and nutrient concentrations. The reduction in soil organic carbon, nitrogen, and phosphorus following forest fires highlights the vulnerability of soil fertility to fire disturbances, with average decreases of 35 %, 25 %, and 15 % respectively. Results further showed that forest fire increases soil pH by an average of 0.5 units and potassium concentration by 30 % due to the deposition of nutrient-rich ash. The result also revealed significant relationships between soil parameters, emphasizing the complex interactions influenced by forest fires. Such information provides a valuable baseline information for future in-depth investigations on the ecological consequences of forest fires. These findings underscore the urgent need for effective forest fire management practices and restoration efforts to safeguard soil health and maintain ecosystem productivity in the Himalayan region. Further research is warranted to elucidate the long-term impacts of forest fires on soil dynamics and ecosystem resilience.

## Declaration of funding

This research did not receive any specific funding.

## CRediT authorship contribution statement

**Himanshu Bargali:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Neha Tiwari:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Dinesh Bhatt:** Writing – review & editing, Supervision, Methodology, Investigation. **R.C. Sundriyal:** Writing – review & editing, Supervision. **V.P. Uniyal:** Writing – review & editing, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests and personal relationships that could inappropriately influence the content of this article.

## Acknowledgements

The authors wish to thank the Director G.B. Pant National Institute of Himalayan Environment (NIHE'), Almora for providing institutional support to conduct this study. Authors express sincere thanks to Dr. G.C. S. Negi, former Scientist G, NIHE', for his encouragement.

## Data availability

All the data generated or analyzed during this study are described in this article.

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