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Research Article

Low-Intensity Wildfire Alters Selected Soil Properties in the Tropical *Shorea robusta* Forest

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Wildfires may impact specific soil properties differently, including positive, negative, or neutral effects. However, due to the absence of uniformity in comprehending how wildfires influence soil nutrients, this research endeavors to scrutinize the particular effect of wildfire on selected soil properties in the tropical *Shorea robusta* forest. We analyzed 42 soil samples obtained from the topsoil of 0–10 cm comprising 21 samples from the fire-affected area and 21 from the fire-unaffected area. The physicochemical parameters of the soil including soil pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorus, and available potassium were examined and compared in two sites. The impact of fire was statistically tested after comparing each variable between the two sites. Using the Mann–Whitney *U* test and the Pearson correlation coefficient, we analyzed the data. The results indicated that the average chemical parameters of the soil except for pH in the fire-affected area (pH = 5.43, SOC = 1.6%, TN = 0.1%, and P = 246.85 $kg{\cdot}ha^{-1}$) were greater than those in the fire-unaffected area (pH = 5.71, SOC = 1.21%, TN = 0.09%, and P = 174.21 $kg{\cdot}ha^{-1}$). There were statistically significant differences in the soil parameters, including pH, SOC, TN, and P, but not with K. The soil pH was reduced in the fire-affected area, with a significant positive correlation with SOC, TN, and K. Overall, the low-intensity wildfire facilitated the proliferation of soil chemical properties in the tropical *S. robusta* forest. Hence, low-intensity wildfire could be a suitable forest management strategy to alter soil nutrient status. Additionally, these findings can aid in enhancing forest fire management strategies for effectively managing the tropical *S. robusta* forest.

1. Introduction

Forest fires are a global phenomenon that affects soil properties and ecosystem health. Fire is regarded as the most detrimental factor in forest ecosystems [1] and is perceived as a global phenomenon influencing soil properties [2]. Fire intensity is classified as low (<100°C), medium (up to 250°C), or high (>350°C) based on heat output per burned area over time [3]. Low-intensity wildfire is an economically efficient forestry method; thus, it is essential to figure out the impacts on soil properties for proper soil management [4]. Forest fires occur mostly during high temperatures and low humidity, and their effects on soil depend on several factors such as fire frequency, severity, and inherent soil properties [5]. The physical, biological, and chemical properties of forest soils vary spatially and temporally. This variation is a result of different biotic and abiotic factors [6]. Fire results in variable soil properties after ameliorating the habitat of the post-fire forests [7]. The effects of surface fire are more complex and comparatively less known than those of above-ground fire [8]. Fire alters the physicochemical properties of the soil, causing nutrient loss [9]. Increased temperature supplies high heat to the mineral content and organic matter [10] and ultimately changes soil chemical properties [11]. Fire affects the soil differently mainly on its inherent properties as well as the frequency and severity of fire [12]. Despite several studies on the effect of fire on soil properties [13], the results of numerous soil properties are highly variable, with positive, negative, or no changes in the soil after the wildfire [14]. Thus, there is a lack of consistency in understanding how forest fire affects soil nutrients.

The well-established relationship between forest vegetation and soil quality involves a mutual influence on physicochemical and biological properties [15]. Additionally, forest soil impacts forest composition, tree growth, and silvicultural properties [16]. The soil's fertility, primarily determined by chemical properties such as pH, organic carbon, total nitrogen, available phosphorus, and available potassium, plays a crucial role [17]. This fertility, in turn, directly influences the recovery of aboveground biomass [18], ultimately shaping the regeneration of forest species [19]. In *S. robusta* forests, forest fires typically manifest as ground fires, often impacting regeneration processes and influencing stand structure. The intricate relationship between forest vegetation and soil underscores the need for a deeper understanding of how wildfires impact soil properties in these ecosystems.

Globally, forest fires have become a significant concern for many countries. In 2015 alone, these fires impacted around 98 million hectares of forest, contributing to 29–37 percent of the global loss of tree cover from 2003 to 2018 [20]. Between 2001 and 2021, Nepal experienced a loss of 13% in total tree cover and 6.78 kilohectares of forest area due to forest fires [21]. The number of reported fires in Nepal varied significantly from 2012 to 2021, reaching an unprecedented level of 6799 reports during 2020-2021 [22]. The impact of a fire on soil varies based on several factors, including the pre-fire environment, fire behavior, timing, and weather conditions before and after the event [23]. Low-intensity fires can enhance soil nutrient levels, particularly for nonvolatile elements like potassium (K), phosphorus (P) [24], and mineral forms of nitrogen, sulphur, and phosphorus [25].

Despite the prevalence of low-intensity forest fire events in Nepal [26], there has been a lack of studies exploring the impact of these fires on the soil. *S. robusta,* the predominant forest species in the Terai tropical forests of Nepal [27], lacks comprehensive studies on how forest fires affect tropical forests globally [28]. Furthermore, there is a research gap in understanding the impact of forest fires on Nepalese tropical forests. Paudel and Sha [29] attempted to identify the physiochemical soil properties of *S. robusta* forests in Eastern Nepal; their study focused on the influence of soil characteristics on vegetation and did not provide results regarding the effects of forest fires on soil properties. Therefore, the study focuses on the tropical *S. robusta* forest in Nepal to understand the effects of wildfire on soil properties. The study aims to assess the impact of low-intensity wildfires on physicochemical properties, nutrient index of *S. robusta*-dominated Terai forest soil in Nepal, and the interrelationships among soil variables. By filling this knowledge gap, the study contributes to evidence-based decision making for wildfire management in the tropical *S. robusta* forest ecosystem.

2. Materials and Methods

2.1. Study Area. Rautahat district is one of the administrative divisions of Madhesh Province (Province 2), situated in the southern part of Nepal. It is located between 26°95′47″ N latitude and 85°31′36″ E longitude (see Figure 1). The study area lies in the lower and upper tropical climatic zones and has an elevation ranging between 122 and 244 meters above mean sea level. The yearly mean temperature of the study area is 28.67°C, which is higher than the national annual average temperature. The region receives about 247.7 millimeters of precipitation and 178.3 rainy days annually. The district has fertile land, and agriculture is the major occupation for livelihood. The forest area covers about 25% of the total district area, and Dhansar Block Forest is one of the forest areas in the district. The average growing stock in the forest is 170.92 cubic meters per hectare, and the average annual increment is 2% [30]. Dhansar Block Forest covers an area of 1,052.92 hectares, with 944.08 hectares effectively managed for utilization. However, the forest frequently experiences wildfires during dry seasons. The forest comprises three main types: tropical mixed Sal forest, Sal-Terai hardwood forest, and riverain forest. The soil types include alluvial loamy soil and sandy loam soil.

3. Methods of Data Collection

The experimental plots ($10 \times 10\,m^2$) for fire-affected areas and fire-unaffected areas were established. A buffer zone of 20 m was established between the fire-affected area and the fire-unaffected area to minimize edge effects. Altogether, 21 soil samples were taken from fire-affected areas and 21 from fire-unaffected areas. Low-intensity wildfires affected about 3 ha of the forest area in April, and measurements were taken in August after 3 months. The color of ash was used to predict fire intensity [2]. Ash color can provide valuable insights into the severity of a fire, as different intensities of fires tend to produce varying shades of ash.

3.1. Soil Sampling. Soil samples were taken from plots subjected to low-intensity wildfires and fire-unaffected areas (absence of forest fire incidences for more than two years). Judgemental soil sampling approach was used to select soil sampling sites ensuring representative coverage of the targeted soil variations in the study area. Hence, soil corers with a 3-inch diameter and 40 cm height were inserted 10 cm deep into the soil to collect the samples. The soil depth of 0–10 cm was chosen for this study because fire generally increases soil temperature and affects its physicochemical properties. The precautions were taken to avoid contamination, such as cleaning or sterilizing equipment between samples. Plant residues and other debris were manually cleared from the soil surface, and about 500 gram of soil was collected. Each soil sample was carefully obtained from the center of each plot and immediately placed in zipper bags, ensuring proper labeling and packaging to maintain sample integrity. The samples were then promptly transported to the laboratory for further analysis. The decision to have a smaller

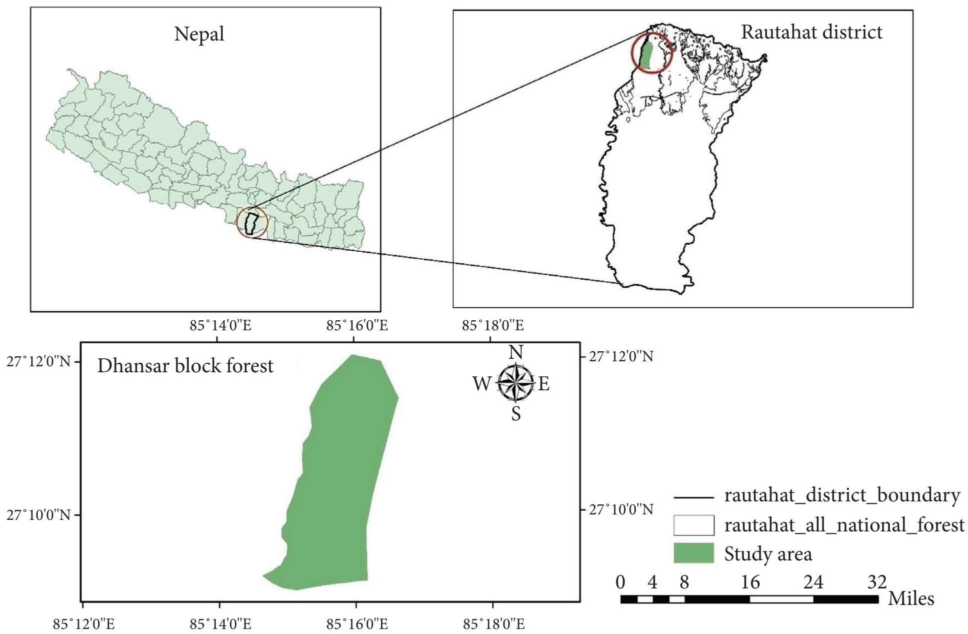

Figure 1: Map showing the Dhansar Block Forest in Rautahat, Nepal.

soil sample size in this study was influenced by several considerations including homogeneity of soil, adoption of targeted sampling approach, and constraints imposed by limited time, budget, and personnel. Ethical considerations, such as obtaining permits from the Division Forest Office, Rautahat, and minimizing damage to vegetation, were taken into account during the soil sampling process in the forest.

3.2. Laboratory Analysis. The collected soil samples were oven-dried at 105°C for 24 hours, crushed, and passed through a 2 mm sieve to separate rough or uneven textures or those consisting of large particles and root materials larger than 2 mm in diameter. The soil parameters, i.e., soil pH, soil organic carbon (SOC), total nitrogen (TN), available phosphorus (P), and available potassium (K), were analyzed. The laboratory analysis of soil was conducted in the Soil and Fertilizer Testing Laboratory, Hetauda, Makwanpur, Nepal. Soil pH was measured using the pH probe with a glass-calomel electrode, keeping a 1 : 1 ratio of soil : water. Soil organic carbon was measured using the Walkley and Black method as outlined by Nelson and Sommers [31]. The total nitrogen (TN) of the soil was measured using the Kjeldahl digestion-distillation method [32]. The available phosphorus content was measured using the modified Olsen bicarbonate method [33]. The flame photometry method was used to measure the amount of available potassium present [34].

3.3. Statistical Analysis. Laboratory data were entered in Microsoft Excel. The Statistical Package for Social Sciences (SPSS, IBM Corporation, version 23) and R version 4.2.3 [35] were used for all the statistical analyses. The Mann–Whitney *U* test was used to determine statistically significant differences in soil properties between the fire-affected and fire-unaffected areas. This nonparametric test was used considering the nonnormality and small sample size of the data. The effect size of the Mann–Whitney *U* test is determined by using the formula given by Cohen [36]. The equation of effect size (r) is referred to as equation (1) in the main text.

$$r = \frac{Z}{\sqrt{N}}. \quad (1)$$

Pearson correlation coefficients were calculated to determine the extent of the relationship among variables. The soil parameters were presented using descriptive statistics such as mean, minimum, maximum, standard error (SE), and variance. The soil pH and nutrients (SOC, TN, P, and K) were differentiated following the Nepal Agricultural Research Council (NARC) [37] (see Table 1).

The soil nutrient index was calculated by following the formula given by Ramamoorthy and Bajaj [38].

$$Nutrient\ index\ (NI) = \frac{(N_L \times 1) + (N_M \times 2) + (N_H \times 3)}{N_T}, \quad (2)$$

where N_L = low and very low class of nutrient status, N_M = medium class of nutrient status, N_H = high and very high class of nutrient status, and N_T = total number of samples.

The resulting soil nutrient index was classified as low (<1.67), medium (1.67–2.33), and high (>2.33).

4. Results and Discussion

4.1. Summary of Soil Variables

4.1.1. Soil pH. Descriptive statistics were calculated to summarize the soil parameters in fire-affected and fire-unaffected areas (see Table 2). The results showed that the

Table 1: Classification of soil fertility parameters by NARC.

Soil parameter	Very low	Low	Medium	High	Very high
SOM (%)	<1	1–2.5	2.5–5	5–10	>10
Total N (%)	<0.050	0.05–0.1	0.1–0.2	0.2–0.4	>0.4
Available P	<10	10–30	30–55	55–110	>110
Available K	<55 Highly acidic	55–110 Acidic	110–280 Slightly acidic	280–500 Neutral	>500 Alkaline
Soil pH	<4.5	4.5–5.5	5.5–6.5	6.5–7.5	>7.5

Table 2: Status of soil fertility parameters in fire-affected and fire-unaffected areas.

Parameters	Fire-affected				Fire-unaffected			
	Mean	SD	Max	Min	Mean	SD	Max	Min
pH	5.43	0.27	5.87	5.04	5.71	0.40	6.5	5.27
SOC	1.6	0.58	2.64	1.15	1.21	0.13	1.43	1.00
TN	0.1	0.01	0.12	0.08	0.09	0.02	0.14	0.07
P	246.85	82.42	343.85	140.7	174.21	45.98	259.91	120.91
K	167.82	53.08	270.97	122.7	187.80	75.64	355.01	122.5

average pH of the fire-affected area was found lower than that of the fire-unaffected area (see Figure 2(a)). In the fire-affected area, the pH ranged from 5.04 to 5.87 with a mean of 5.43 with a standard deviation (0.27) showing acidic category of soil pH (see Table 1), while in the fire-unaffected area, it ranged from 5.27 to 6.5 with a mean of 5.71 with a standard deviation (0.4) depicting slightly acidic soil pH (see Table 2). This showed that the fire-affected area was comparatively more acidic than the fire-unaffected area. Their difference was statistically significant ($p < 0.1$).

Soil pH is regarded as the "master soil variable" influencing myriad biogeochemical processes that affect plant growth [39]. The pH of the soil in the study area was found to be slightly more acidic in the fire area. Soil pH >6.5 is found occasionally in *S. robusta* forests in the tropical region of Nepal [40]. In the current study, the pH values observed (ranging from 5.27 to 6.5) in the fire-unaffected areas were quite similar to those reported by Sigdel [41] in Chitwan National Park (ranging from 5.90 to 6.42). However, Singh and Singh [42] documented higher pH range for *S. robusta*-dominated central Himalayan forests (ranging from 6.7 to 6.8). The pH range of 4.5–5.5 is propitious for *S. robusta* regeneration [29]. In line with this reference, our study found more samples belonging to the acidic category and a decrease in the mean pH in the fire-affected area. These findings imply that low-intensity forest fires create suitable soil conditions, specifically in terms of acidity, for *S. robusta* regeneration. The observed reduced pH after fire aligns with the findings of McLauchlan et al. [8]. Forest fires with soil temperatures >200°C incinerate organic matter and give off char compounds, resulting in ash formation and an increased pH. However, low-intensity wildfires burn the forest floor below 100°C, which may be due to the desiccation and heating of the soil surface favoring proton-reducing oxidation reactions [43]. This could explain the decrease in pH observed in the fire-affected area. This is also supported by the positive correlation between soil organic carbon and soil pH in the fire-affected area. Alcañiz et al. [44] concluded that there was a significant increase in pH following prescribed fire in the *Pinus halepensis* forests in Spain. In contrast, other studies reported an unaffected pH after forest fires [45, 46].

4.2. Soil Organic Carbon (SOC). Soil organic carbon (SOC) has been an extensively studied soil parameter due to its importance for soil quality [47]. SOC levels can vary significantly and depend on various factors such as the duration of the fire, the amount of available biomass, its moisture content, and intensity of the fire [48]. Low-intensity wildfires usually enhance macronutrients for plant growth [49]. The major effects of fire on the soil's organic materials are confined to the upper layer of the forest floor. Loss of soil organic carbon (SOC) begins at around 200–250°C, while complete combustion of SOC occurs at temperatures ranging from 460 to 500°C [45]. The present study showed that the average soil organic carbon content was statistically significantly higher ($p < 0.1$) in the fire-affected area than in the fire-unaffected area; however, the relation was not statistically significant at $p = 0.05$ (see Figure 2(b)). In the fire-affected area, the SOC ranged from 1.15 to 2.64% with a mean of 1.6% with a standard deviation (0.58), whereas the SOC ranged from 1 to 1.43% with a mean of 1.21% with a standard deviation (0.13) in the fire-unaffected area (see Table 2). Taking into account that soil organic matter (SOM) comprises 58% organic carbon, SOM levels in the fire-affected area (2.75) fall within the medium category, while they fall into the low category in the fire-unaffected area (2.23) (see Table 1).

The significance of soil organic carbon on the chemical properties of soil is well documented. In addition to the aforementioned studies, Gautam and Mandal [50] also reported similar pH values (ranging from 1.22 to 1.46) in the *S. robusta* forest of Sunsari district. These values were comparable to the pH values observed in the fire-unaffected region of our study. The effects of forest fires on soil can vary widely, and study indicates that low-intensity fires may cause little to no change or even an increase in soil organic carbon (SOC), while high-intensity fires generally lead to a decrease

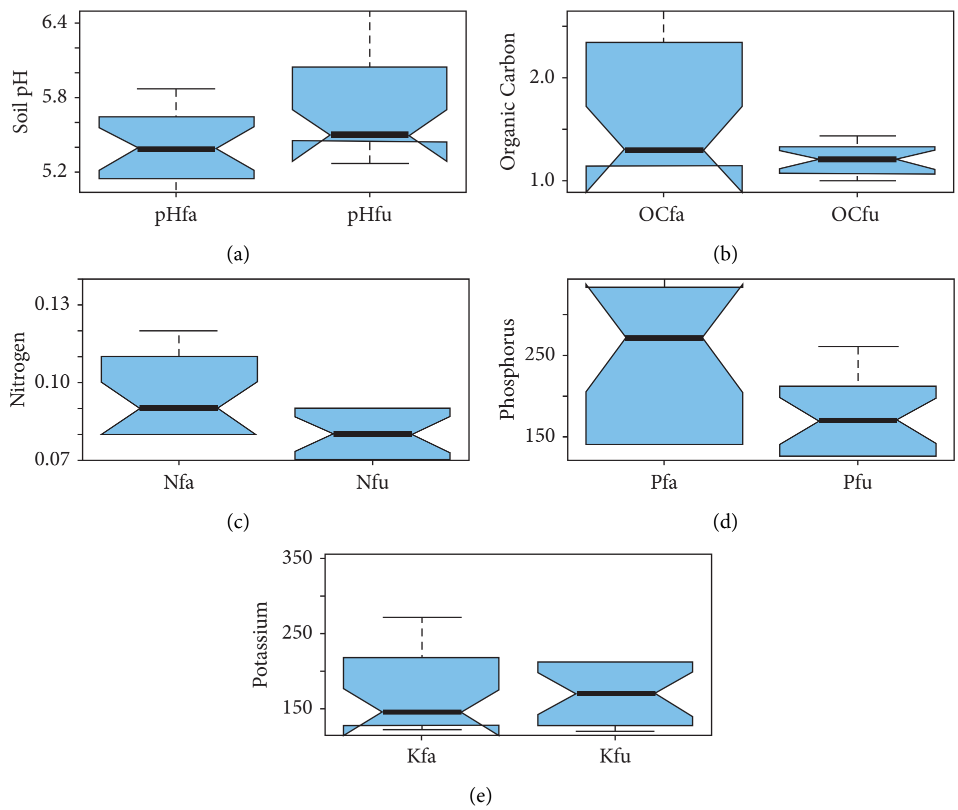

Figure 2: Boxplots showing soil fertility parameters in fire-affected and fire-unaffected areas.

in SOC [3]. Similarly, our study found the increased SOC content after low-intensity wildfire. Also, the observed increment of soil organic carbon shortly after a forest fire corresponds with the findings by Johnson and Curtis [51]. During burning, low temperatures in the top centimeter of mineral soil may have contributed to incomplete combustion of organic matter, or necromass added to the soil could have affected the results [52]. In our study, the burned site was not completely blackened, suggesting that the heat achieved was inadequate to completely deplete organic soil material from the forest floor, indicating low-intensity fire [53]. The estimated burning time for each plot was approximately 30 minutes.

4.3. Total Nitrogen (TN). Nitrogen (N) is often the most limiting nutrient in forests [54]. The average total nitrogen content in soil was found to be higher (0.1%) in the fire-affected area than the fire-unaffected area (0.09%), while the range was found to be 0.08 to 0.12% and 0.07 to 0.14%, respectively (Figure 2(c)). Likewise, the standard deviations for the both areas were low (see Table 2). Similarly, the average total nitrogen was found to be medium in the fire-affected areas, where it was determined to be low in the fire-unaffected areas (see Table 1). They were statistically significant to each other ($p < 0.05$). It is important to study how fire affects soil nitrogen since it is considered the most limiting nutrient in tropical ecosystems [55], with multiple potential factors contributing to opposing effects [14]. Gautam and Mandal [50] reported similar values of total nitrogen (ranging from 0.10% to 0.14%) observed in the fire-unaffected region of our study. The finding of increased nitrogen content in the fire area is in agreement with the study from an Illinois oak-dominated forest [56]. Similarly, Liu et al. [57] reported increased TN in the grassland vegetation after a low-intensity fire. However, Akburak et al. [4] found no impact on TN after low-intensity fire. On the contrary, Francos et al. [58] conducted a study in a forest consisting of *Pinus halepensis* and *Quercus ilex* trees in Spain and found that forest fires led to a significant decrease in the amount of total nitrogen present in the top layer of soil. According to Muqaddas et al. [59], the main cause of nitrogen loss in mineral soils following forest fires is volatilization. Since soil temperature is lower in low-intensity fires, total nitrogen may increase due to the accumulation of nitrogen-rich compounds from partial combustion and the assimilation of residue onto the forest floor [60]. Forest fires can lead to higher soil temperatures and pH levels, which affect the levels of inorganic nitrogen (such as NH_4^+ and NO_3^-) in the soil through mineralization and nitrification processes, as shown by studies by Calvo et al., Verma and Jayakumar [61–63]. Although some nitrogen may be lost through volatilization during forest fires, the remaining nitrogen can be mineralized to NH_4^+-N and further nitrified to NO_3^--N under suitable conditions, as observed by study by Agbeshie et al. [54]. As a result, there is often an increase in the amount of available nitrogen following a forest fire.

However, SOC and TN can be varied along the slopes and soil profile which may be due to greater loss of soil in upper slopes and vice versa [64].

4.4. Available Phosphorus (P). Phosphorus is the second most limiting nutrient for plants, needed in the form of phosphate [65]. After a forest fire, organic phosphorus in organic matter transforms into available orthophosphate [66]. The results showed a higher scattering value of the available phosphorus ($kg \cdot ha^{-1}$) in the fire-affected area than in the fire-unaffected area (see Figure 2(d)). They were statistically significantly different ($p < 0.05$) from each other. The available phosphorus ranged from 120.91 to 343.85 $kg \cdot ha^{-1}$with a mean value (246.85 $kg \cdot ha^{-1}$) and SD (82.42) in the fire-affected area, while it ranged from 120.91 to 259.91 $kg \cdot ha^{-1}$with a mean value (174.21 $kg \cdot ha^{-1}$) and SD (45.98) in the fire-unaffected area (see Table 2). As shown in Table 1, the average available phosphorus was very high in both areas.

Many studies have also focused on the availability of phosphorus and total nitrogen while addressing the impacts of low-intensity wildfires. Available or exchangeable phosphorus is also one of the limiting macronutrients in different forest ecosystems [14]. Our study found a significant increase in available phosphorus in the fire-affected area, which aligns with the findings of Turrion et al. [67]. In line with our findings, Moya et al. [68] also discovered comparable results, noting that in the 10 cm A horizon, the *P. halepensis* forest exhibited notably higher levels of available phosphorus compared to the control plot. Following a low-intensity wildfire in grasslands, Liu et al. [57] found elevated available P concentrations in the top 10 cm of soil. According to Caon et al. [3, 44, 66], the increase in available phosphorus in the A horizon resulted from organic phosphorus mineralization, ash deposition on the soil surface, decreased phosphorus losses due to increased vaporization, and the formation of apatite (insoluble phosphorus) in the presence of calcareous substances [69], while Vergnoux et al. [70] attributed the increase to the mineralization of organic phosphorus.

4.5. Available Potassium (K). Potassium (K) plays a crucial role in the productivity and sustainability of numerous forests [71]. The present results showed a medium concentration in both the fire-affected area and the fire-unaffected area (see Figure 2(e)). They were not statistically significantly different to each other. The average available potassium (K) for the fire-unaffected area was found to be 187.8 $kg \cdot ha^{-1}$ with a standard deviation of 53.08, whereas in the fire-affected area, the value was found to be 167.22 $kg \cdot ha^{-1}$ with a standard deviation of 75.64 (see Table 2). Considering the criteria given in Table 1, the average available potassium in the both areas was medium denoting no statistically significant difference after the incident of forest fire in potassium content.

Contrary to our finding, Ekinci [72] found a significant increase in available K concentrations in the burned soils compared to the unburned control plots. Similarly, Khaki et al. [73] also found a significant increase in available K concentrations in the burnt plot in blue pine ecosystems. Also, Maynard et al. [74] observed that burnt plots in a boreal stand had significantly higher levels of K^+ in the A horizon compared to unburnt plots. However, other researchers have documented no change or a decrease in exchangeable cations following fires. Liu et al. [57] found a negligible difference in K^+ levels between pre- and post-wildfire soils in grassland vegetation. Similarly, Johnson et al. [75] discovered insignificant K^+ levels in a mixed conifer forest before and after a wildfire. Exchangeable cation losses may occur as a result of ash erosion and leaching, as well as plant absorption during post-fire succession, due to their high vaporization thresholds [3].

However, the available P and K can be attributed from ashes and charcoal after burning, which may take some years to return to the pre-levels, even 2 years [76].

5. Correlation Analyses

The soil parameter's correlations between fire-affected and fire-unaffected areas are shown in Figure 3. No significant correlation between P and pH was observed, while negative correlation was noted with TN (-0.10) and positive low correlation with SOC (0.14) in the fire-affected areas. Meanwhile, SOC exhibited positive correlations with pH (0.56), TN (0.66), and K (0.95) in this region. Likewise, high positive correlations were observed between P and pH (0.96), as well as TN (0.90), between K and pH (0.95), TN (0.97), and P (0.96) in fire-unaffected areas. However, a low correlation between K and P (0.28) was found in the fire-affected area. Similarly, in the fire-affected area, there were high correlations between K and pH (0.69), SOC (0.95), and TN (0.78), whereas a negative correlation with SOC (-0.20) was observed in the fire-unaffected area. Likewise, TN showed similar patterns with pH in both fire-affected (0.76) and fire-unaffected areas (0.88) depicting high correlations. In contrast, SOC showed positive correlation with pH at fire-affected area, while it showed negative correlation at fire-unaffected areas (see Figure 3).

Fire burns organic matter, deposits ash on the soil, and significantly alters soil chemistry by introducing ash and partially burned organic material [77]. In general, contrasting relationships between the soil variables can be observed in the fire-affected area and the fire-unaffected area. Soil organic carbon contents were moderately positively correlated (0.56) with soil pH in the fire-affected area; however, a nonsignificant negative correlation (−0.04) was found with the soil pH of the fire-unaffected area (see Table 3).

Total nitrogen of the fire-affected area had a significantly high positive correlation with soil pH (0.76) and SOC (0.66) of the fire-affected area respectively; however, a negative correlation (−0.28) was found only in SOC in the fire-unaffected area (see Table 3). However, available phosphorus was not significantly correlated with the soil pH, SOC, or TN in the fire-affected area; available phosphorus had a significantly positive correlation with soil pH (0.95) and TN (0.90) but not with the SOC in the fire-unaffected area (see Table 3). Available potassium was significantly positively correlated only with soil pH (0.69), SOC (0.95), and TN (0.78) in the fire-affected area (see Table 3). On the other hand, the striking result regarding relationships among variables was that available potassium showed a nonsignificant relationship with SOC and a significantly positive correlation (0.95) with available phosphorus in the fire-unaffected area (see Table 3).

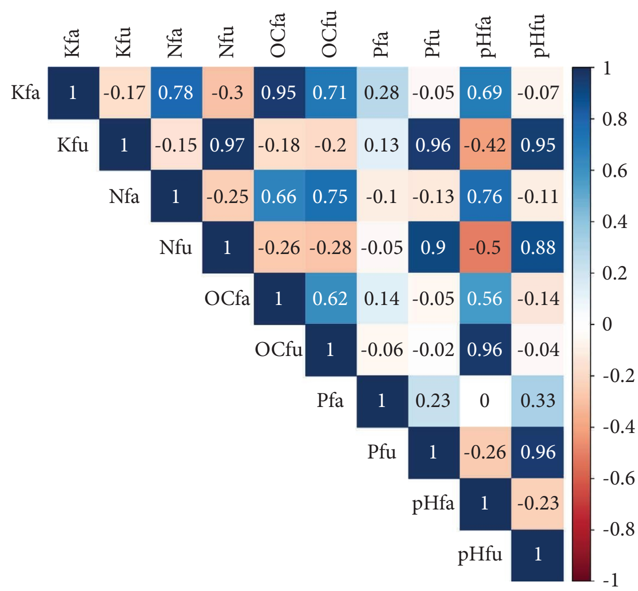

FIGURE 3: Pearson correlation coefficients (considering all variables and both fire-affected and fire-unaffected groups together) using corrplot package in R. Deep blue color indicates stronger positive correlations, while the deep red color indicates stronger negative correlations. In this representation, 'fa' signifies as fire-affected area and 'fu' signifies as fire-unaffected area. K = available potassium; N = total nitrogen; OC = soil organic carbon; P = available phosphorus; and pH = soil pH.

TABLE 3: Correlation matrix between soil variables.

	pH	SOC	TN	*P*
Fire-affected area				
SOC (%)	0.56**			
TN (%)	0.76**	0.66**		
P (kg·ha^{-1})	0.00	0.13	−0.10	
K (kg·ha^{-1})	0.69**	0.95**	0.78**	0.27
Fire-unaffected area				
SOC (%)	−0.04			
TN (%)	0.88**	−0.28		
P (kg·ha^{-1})	0.95**	−0.01	0.90**	
K (kg·ha^{-1})	0.94**	−0.20	0.97**	0.95**

**Correlation is significant at the 0.01 level.

Gautam and Mandal [50] observed a strong correlation between soil organic carbon (SOC) and total nitrogen in the *S. robusta* forest of Sunsari district. In the forests of Udayapur district, Paudel and Sah [29] identified a positive association between soil organic carbon (SOC) and total nitrogen, while Chauhan et al. [78] found the same in Chitwan district. However, our study found a positive correlation in the fire-affected area which indicates the suitable habitat condition for *S. robusta* forest after post-fire effect.

6. Comparisons of Soil Parameters between Fire-Affected Area and Fire-Unaffected Area

Significant statistical disparities at p <0.1 were observed in soil pH between the fire-affected area (median = 5.39, n = 21) and the fire-unaffected area (median = 5.50, n = 21), U = 135, z = 2.16, p = 0.03, and with a small effect size of r = 0.33 (see Table 4). Similarly, there were statistically significant differences at p <0.1 in soil organic carbon between the fire-affected area (median = 1.3, n = 21) and the fire-unaffected area (median = 1.21, n = 21), U = 148.5, z = 1.82, p = 0.07, and with a small effect size of r = 0.28 (see Table 4). Likewise, significant disparities at p <0.05 were noted in total nitrogen between the fire-affected area (median = 0.09, n = 21) and the fire-unaffected area (median = 0.08, n = 21), U = 135, z = 2.21, p = 0.03, and with a small effect size of r = 0.34 (see Table 4). Correspondingly, significant differences at p <0.05 were observed in available phosphorous between the fire-affected area (median = 270.97, n = 21) and the fire-unaffected area (median = 168.93, n = 21), U = 112.5, z = 2.73, p = 0.01, with a small effect size of r = 0.42 (see Table 4). The results indicated a higher average available potassium in the fire-unaffected area; however, no significant differences were found in available potassium between the fire-affected area (median = 144.92, n = 21) and the fire-unaffected area (median = 168.93, n = 21), U = 184.5, z = 0.91, p = 0.36, with a small effect size of r = 0.14 (see Table 4).

The study found nonsignificant effects of low-intensity wildfires on available potassium. Coates et al. [79] found, analogous to our study, that available potassium was less in fire-affected areas. On the contrary, the decrease in available potassium was inconsistent with the findings reported by Scharenbroch et al. [52]. The finding may be attributed to the loss of nutrients by volatilization due to the lower volatilization temperature (774°C) of potassium. Dhungana et al. [80] concluded that low-intensity wildfires can serve as a valuable means of regenerating seedlings of *S. robusta*. Thus, the positive effect may be attributed to the enhanced physico-chemical properties of the soil following the post-fire effect.

6.1. Nutrient Index of Soil Parameters. The study analyzed the soil nutrient levels of soil organic carbon, total nitrogen, available phosphorus, and available potassium (see Table 5). The nutrient index of all soil parameters was calculated by following equation (2). The results showed that both types of areas had low nutrient index levels for soil organic carbon and total nitrogen. Low nutrient index levels for soil organic carbon and total nitrogen in both areas suggest a deficiency of these nutrients in the soil. Soil organic carbon is essential for maintaining soil fertility and overall soil health. It contributes to soil structure, water retention, and nutrient cycling. The low levels observed in both areas may indicate a potential limitation in these important soil functions. Similarly, total nitrogen is a crucial nutrient for plant growth and development. It is an integral component of proteins and enzymes necessary for various metabolic processes. The low nutrient index levels of total nitrogen imply that the availability of this nutrient in the soil is limited. This can have implications for plant productivity, as nitrogen is often a limiting factor in plant growth. On the other hand, available potassium exhibited medium nutrient index levels in both the fire-affected and fire-unaffected areas. Potassium is essential for plant nutrient uptake, enzyme activation, and regulation of various physiological processes. The medium levels suggest a moderate availability of potassium in the soil of both areas, which can

Table 4: Mann–Whitney *U* test table showing effect size.

Parameters	Plot	Median	Mann–Whitney (*U*)	z	*p*	Effect size (*r*)
pH	FA	5.39	135.00	2.16	0.03*	0.33
	FU	5.50				
SOC (%)	FA	1.30	148.50	1.82	0.07*	0.28
	FU	1.21				
TN (%)	FA	0.09	135.00	2.21	0.03**	0.34
	FU	0.08				
P ($kg{\cdot}ha^{-1}$)	FA	270.97	112.50	2.73	0.01**	0.42
	FU	168.93				
K ($kg{\cdot}ha^{-1}$)	FA	144.92	184.50	0.91	0.36	0.14
	FU	168.93				

FA denotes fire-affected area, whereas FU denotes fire-unaffected area. ** indicates the significance at $p < 0.05$. * indicates the significance at $p < 0.1$.

Table 5: Nutrient indices between fire-affected area and fire-unaffected area.

Soil parameters	Fire-affected area		Fire-unaffected area	
	Values	Index	Values	Index
SOC (%)	1.14	Low	1	Low
TN (%)	1.42	Low	1.14	Low
P (kg/ha)	3	High	1	Low
K (kg/ha)	2	Medium	2	Medium

potentially support plant growth and productivity to some extent. Soil phosphorus (P) is a significant indicator of soil fertility and quality, and it is strongly linked to soil productivity [81]. In our study, we found that the available phosphorus levels were high in the fire-affected area, indicating a high nutrient index. Conversely, in the fire-unaffected area, the available phosphorus levels were low, indicating a low nutrient index. This indicates that low-intensity wildfire potentially contributes to soil fertility and productivity in the fire-affected areas. Overall, the results indicate a deficiency of soil organic carbon and total nitrogen in both the fire-affected and fire-unaffected areas, highlighting the need for nutrient management strategies to enhance soil fertility. The moderate availability of potassium and high presence of phosphorus suggest a relatively better condition in terms of this nutrient. These findings emphasize the importance of addressing nutrient imbalances and implementing appropriate soil management practices to improve soil fertility and support sustainable agricultural or ecosystem productivity in both areas. Thus, low-intensity fire plays a crucial role in the functioning of tropical forest ecosystem. However, it is important to plan and manage fires carefully to ensure that they do not have negative impacts on forest soils. The possible reason behind high nutrient index at fire-affected area might be high chances of deposition of ash after burning available biomass. The nutrient-rich biomass may not get chance to release at once at the fire-unaffected area. This finding has been supported by many previous studies like Agbeshie et al. [77] and references cited there in.

7. Conclusion

The study found that post-wildfire effects on selected soil properties were variable. Specifically, the low-intensity wildfire had a positive impact on soil pH, soil organic carbon, total nitrogen, and available phosphorus for studied species, while the effects on available potassium were significantly unchanged. The soil pH in the fire-affected area was slightly more acidic, indicating favorable conditions for the regeneration of tropical *S. robusta*. Similar levels of soil organic carbon and total nitrogen were observed in both areas with low nutrient indices, and available potassium levels were medium in both areas. Notably, available phosphorus levels were higher in the fire-affected area compared to the fire-unaffected area. This study offers valuable insights into the effects of low-intensity wildfires on selected soil properties in *S. robusta* forests in Nepal. As such, forest management strategies should consider the positive post-fire effects of low-intensity wildfires to create favorable conditions for the regeneration of tropical *S. robusta*. Further research, utilizing a chrono-sequence approach with repeated wildfires of different severities, especially in tropical regions, is necessary to better understand both the short-term and long-term impacts on soil properties.

Data Availability

The data used to support the findings of this study are available from corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

BPD collected data, analyzed samples and data, writing the draft and final manuscript. VTC conducted data analysis and finalized the draft manuscript. CBB reviewed and edited the manuscript. SPS reviewed and revised the manuscript.

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