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POST-WILDFIRE ALTERATIONS IN SOIL PHYSICAL PROPERTIES OF COASTAL SANDY SOILS IN TERENGGANU, MALAYSIA

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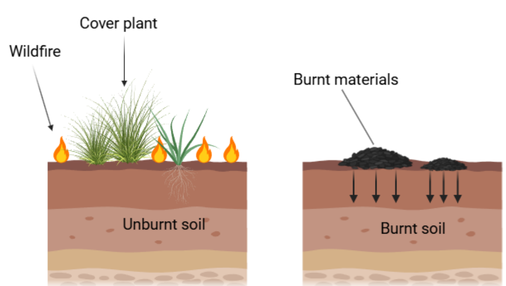
Graphical abstract



Abstract

Wildfires present considerable environmental concerns, especially in susceptible coastal habitats characterized by sandy soils. This research examines the impact of surface wildfires on soil physical characteristics at five coastal locations in Terengganu, Malaysia: Gong Badak, Jalan Pantai Tok Jembal, Bandar Kuala Nerus, Taman Baiduri, and Kampung Kuala Tengah. Every site underwent wildfire incidents that resulted in distinct burnt and unburned areas. Eight essential soil parameters were evaluated: water density, soil porosity, wet and dry bulk density, saturated hydraulic conductivity, electrical conductivity, cohesion, and organic matter content. Standardized field and laboratory methodologies were employed, incorporating Decagon sensors, pocket penetrometers, and the loss-on-ignition approach. The results indicated that wildfire substantially modified many soil properties in a site-specific manner. For example, Bandar Kuala Nerus demonstrated significant decreases in saturated hydraulic conductivity and soil cohesiveness, whereas Gong Badak revealed enhanced porosity and diminished bulk density in burned soils. Certain observations, like increased porosity following a fire, deviated from traditional assumptions, presumably due to the sandy soil environment. The study emphasizes the intricate and specific effects of wildfires on soil physical conditions, underscoring the necessity of customized land management practices in post-wildfire recovery initiatives. The results provide significant insights into fire-soil interactions in tropical coastal ecosystems, where data are scarce.

Keywords: Wildfire impact, burnt soil, coastal sandy soil, post-fire soil assessment, soil hydrology

Abstrak

Kebakaran tanah merupakan isu alam sekitar yang ketara, terutamanya di habitat pesisir yang terdedah dan dicirikan oleh tanah berpasir. Kajian ini meneliti kesan kebakaran permukaan terhadap ciri fizikal tanah di lima lokasi pesisir di Terengganu, Malaysia: Gong Badak, Jalan Pantai Tok Jembal, Bandar Kuala Nerus, Taman Baiduri, dan Kampung Kuala Tengah. Setiap lokasi mengalami insiden kebakaran yang menghasilkan kawasan terbakar dan tidak terbakar yang jelas. Lapan parameter penting tanah dinilai: ketumpatan air, porositi tanah, ketumpatan pukal basah dan kering, kekonduksian hidraulik tepu, kekonduksian elektrik, kekuatan lekatan tanah (kohesi), dan kandungan bahan organik. Kaedah standard lapangan dan makmal digunakan, termasuk sensor Decagon, penetrometer poket, dan kaedah pembakaran kehilangan-penyalaan (loss-on-ignition). Hasil kajian menunjukkan bahawa kebakaran hutan telah mengubah banyak ciri tanah dengan ketara secara spesifik mengikut lokasi. Contohnya, Bandar Kuala Nerus menunjukkan penurunan ketara dalam kekonduksian hidraulik tepu dan kohesi tanah, manakala Gong Badak menunjukkan peningkatan porositi dan pengurangan ketumpatan pukal dalam tanah terbakar. Beberapa pemerhatian, seperti peningkatan porositi selepas kebakaran, bertentangan dengan jangkaan lazim, mungkin disebabkan oleh persekitaran tanah berpasir. Kajian ini menekankan kesan kebakaran hutan yang rumit dan khusus terhadap keadaan fizikal tanah, serta keperluan amalan pengurusan tanah yang disesuaikan dalam usaha pemulihan selepas kebakaran. Hasil kajian ini menyumbang kepada pemahaman interaksi antara kebakaran dan tanah di ekosistem pesisir tropika yang masih kurang dikaji.

Kata kunci: Kesan kebakaran hutan, sifat fizikal tanah, tanah berpasir pesisir, penilaian tanah pasca-kebakaran, hidrologi tanah

1.0 INTRODUCTION

Wildfires are widely acknowledged as significant disturbances that affect the ecological and physical characteristics of terrestrial ecosystems. Worldwide, wildfire occurrences have increased due to climatic changes and human activities, impacting vegetation, air quality, and particularly soil systems [1], [2]. In Malaysia, while wildfires are not as thoroughly researched as in temperate places, they sporadically occur during extended dry seasons and can significantly transform the environment, especially in coastal and sandy areas like those in Terengganu.

Soil is an essential natural resource that facilitates plant growth, regulates hydrology, and provides habitat for diverse organisms. Wildfires can cause various physicochemical changes in soil, influenced by the fire's intensity and duration, existing soil conditions, and vegetation type. Prior research has documented alterations in soil temperature patterns, a decrease in soil organic matter (SOM), and disturbances in soil structure subsequent to fire incidents [2], [3]. These alterations can subsequently affect critical soil physical qualities like bulk density, porosity, water retention, hydraulic conductivity, and cohesion.

Coastal and sandy soils, such as those in the Kuala Nerus and Kuala Terengganu areas, are particularly vulnerable to disturbance due to their low organic content and fragile structural integrity. The beach-ridge coastal plains of Terengganu include sandy, non-saline soils and predominantly sustain coastal scrub and grass species. In the dry season, these regions are prone to surface wildfires that can incinerate protecting vegetation layers, so exposing the soils to direct heat and potentially altering their physical properties [4].

This study assesses the effects of wildfire on eight essential soil physical parameters: water density, soil porosity, wet and dry bulk density, saturated hydraulic conductivity, soil electrical conductivity, soil cohesion, and organic matter content. These indicators are essential for evaluating soil functionality, especially in post-fire recovery and land management strategies. Previous studies indicate that fire may elevate soil bulk density by the disintegration of aggregates, while reducing porosity in sandy soils by disrupting weak structural links [4], [5]. Saturated hydraulic conductivity frequently diminishes after a fire due to the formation of hydrophobic condition or the obstruction of airspace by burnt particles [6].

In Malaysia, lack of prove regarding the consequence of wildfires on the physical qualities of coastal sandy soils. This study aimed to address that gap by performing fieldwork at five sites in Terengganu: Gong Badak, Jalan Pantai Tok Jembal, Bandar Kuala Nerus, Taman Baiduri, and Kampung Kuala Tengah. Every site underwent surface wildfires that resulted in identifiable burned (B) and unburned (UB) regions. By sampling both areas, a comparative analysis of soil conditions post-wildfire was conducted to identify site-specific impacts and overarching patterns.

Ultimately, comprehending the magnitude and characteristics of soil physical alterations induced by wildfire in these places might guide future soil conservation policies, rehabilitation initiatives, and fire control methods in Malaysia's coastal ecosystems. This research enhances the broader discussion on fire-soil interactions, especially with tropical and subtropical sandy soils.

2.0 METHODOLOGY

2.1 Study Area

The field study was executed in five locations in the region of Terengganu, Malaysia: Gong Badak, Jalan Pantai Tok Jembal, Bandar Kuala Nerus, Taman Baiduri, and Kampung Kuala Tengah, all situated within the Kuala Nerus/Kuala Terengganu districts. These locations exhibit a tropical monsoon climate. The annual temperature (mean) of approximately 28–30 °C and 2900 to 3600 mm as in the yearly precipitation [7], [8]. The soils were primarily sandy, constituting the beach-ridge coastal plain, and are non-saline (electrical conductivity typically <0.2 dS/m) [9]. Each site underwent a surface wildfire during the dry season, resulting in a burned region (B) adjacent to an unburned control area (UB). Post-fire measurements were conducted at both the burned plots and the adjacent unburned plots at each location. Before the fire, the vegetation consisted of coastal scrub and grass; after the fire, the scorched areas were predominantly bare, with some burnt debris. This study environment facilitated a comparison of soil physical parameters between wildfire-affected and unaffected conditions at each site. The land study area for each site was found to be approximately greater than 400 m^2 burnt surface soil based on visual inspection.

2.2 Soil Sampling and Preparation

Soil obtained at the surface topsoil (0–10 cm) in specified field plots. At each site, stainless steel soil sampler was used to collect undisturbed core samples and the sampler has a specified 0.05015 m height and an internal 0.0503 m diameter The sampler's cross-sectional area and volume were determined to be 1.987×10^{-3} m^2 and 9.965×10^{-5} m^3, respectively. Samples were promptly packaged to reduce moisture loss during transit to the laboratory.

2.3 Soil Moisture, Soil Electric Conductivity, Soil Temperature

Soil moisture, electric conductivity and temperature were monitored in situ at each sampling location before the cores were extracted. A handheld soil thermometer was placed to the depth of soil to measure soil temperature (°C) in triplicate, which was then averaged and converted to Kelvin (K). A portable soil moisture sensor and electric conductivity (GS3, Decagon) with reading meter was employed to assess volumetric soil water content (m^3/m^3) and soil electric conductivity (dS/m) at the soil, with three readings recorded and averaged for each plot [10].

2.4 Soil Water Density

The density of water was calculated according to the site's typical temperature utilizing recognized thermodynamic water density tables. This number, expressed in kg/m^3, is influenced by temperature and was utilized as an input for future computations of soil density. Estimated values at 20–30 °C varied between 997 and 995 kg/m^3 [11].

2.5 Wet Bulk Density and Dry Bulk Density

The total moist mass of each soil-filled core (comprising the cylinder and net base) was measured with an electronic scale (±0.01 g accuracy). The moist mass was determined by subtracting sampler unit that was comprising the cylinder and net base. Wet bulk density was determined by dividing the mass of wet soil by the core volume, whereas the dry bulk density estimated by subtracting water mass from the measured soil moisture content before dividing by core volume. The data were documented in kg/m^3. Alternative approach in estimating soil bulk density can also be found in Tranter *et al*. [12].

2.6 Soil Porosity

Soil porosity was determined using the formula of unity minus by the ratio of soil bulk density and soil particle density [13], [14], with the particle density set to be 2650 kg/m^3 [15], a standard value for mineral soils. Porosity values were denoted in m^3/m^3.

2.7 Saturated Hydraulic Conductivity

Falling-head method was used to measure the saturated hydraulic conductivity via [16], [17]. Each soil core was saturated by gradual immersion in water for a few minutes, unit the upper soil surface begins to wet. A vertical standpipe with a diameter of 0.0159 meters was affixed to the apex of the core. Water was permitted to permeate the soil, and the reduction in water level from the beginning height to the final height was recorded over time. Three trials were performed for each sample and subsequently averaged. This technique is commonly utilized for ascertaining saturated hydraulic conductivity in coarse-textured and sandy soils [6]. The findings were computed in meters per second.

2.8 Particle Size Distribution

Forty grams of each soil were placed in a 500 mL polypropylene bottle, to which 5 g of sodium hexametaphosphate and 300 mL of deionized water were added for dispersion via continuous shaking for a day. The configuration of the device conformed to the procedure specified in the manufacturer's recommendation. The sample was consistently agitated to maintain distribution using a hand plunger for one minute, after which the PARIO device was immediately immersed in the solution. The PARIO meter possessed a measurement depth of 18 centimeters. The measurement duration in a suspension cylinder (1 L) was set at 24 hours, and the first 30 seconds reading taken. The silt and clay content segregation achieved by measurement after a day. The fractions of sand were inputted into the Pario software interface after sieving via 500, 250, and 53 µm. The Pario software independently modifies an inverse model on measured pressure data and externally obtained user provide sand fractions to determine the soil particle size distribution [18], [19]. Comparable results between Pario system and hydrometer method [20]. The soil texture at five locations as tabulated in Table 1.

Table 1 Soil texture of the soil at different locations

Locations	GPS Coordinate	Soil texture	
		Burn	Not Burn
Gong Badak	5.3885321, 103.0804440	Sand	Sand
Jalan Pantai Tok Jembal	5.402328, 103.099615	Sand	Sand
Bandar Kuala Nerus	5.3960831, 103.0660003	Silty Clay Loam	Loamy Sand
Taman Baiduri	5.408453, 103.070444	Sand	Sand
Kg Kuala tengah	5.089932, 103.266633	Sandy Loam	Sand

2.9 Soil Organic Content

The soil organic content as in soil organic matter (SOM) was assessed in the disturbed samples utilizing the loss-on-ignition (LOI) method. Each sample was sieved using a 2 mm sieve. A 10 g soil sample was placed in a ceramic cup and 24 hours oven dry at 105 °C to eliminate moisture. After chilling in a desiccator, the soil was weighed and subsequently using furnace for 4 hours incineration at 550 °C. The crucible was cooled and reweighed to get the ash weight. The mass loss of ignition is ascribed to the oxidation of organic material. The proportion of mass lost on igniting was used to calculate SOM content, with findings shown on a dry weight basis. The LOI method is a conventional procedure [21] that yields an estimate of total organic matter, which correlates significantly with soil organic carbon.

2.10 Soil Cohesion

A pocket penetrometer measured soil cohesion (mechanical strength) in the field [22], [23]. Pushing a tiny piston into the soil surface measures unconfined compressive strength quickly with this handheld device. For each plot, three penetrometer readings were recorded at 0-10 cm depth on flat, representative places, avoiding stones or roots. The mean penetrometer resistance per plot was calculated by averaging the data (kg/cm²).

3.0 RESULTS AND DISCUSSION

The estimated p-value was obtained by comparing the parameters of burnt and unburnt soils at a specific site. A p-value greater than 0.05 is a good indication for no statistically significant difference between the burnt and unburnt soils for the parameter being analyzed. Conversely, if the p-value is less than 0.05, it suggests a statistically significant difference between burnt and unburnt soils. This implies that burning has influenced the parameter, leading to a significant change compared to the unburnt soil.

As stated in the previous section, there were eight parameters measured on-site. Water density was one of the parameters measured at wildfire sites. Table 2 shows Gong Badak has a p-value above 0.05, which signifies wildfire does not have significant effect on the site that the change in the water density can be considered insignificant. However, the other four sites such as Jalan Pantai Tok Jembal, Bandar Kuala Nerus, Taman Baiduri, Kampung Kuala Tengah, have p-values less than 0.05 that indicates wildfire influences the water density of the sites. The variation in water density among locations may be attributed to differences in vegetation cover, soil texture, and burn severity. Sites like Jalan Pantai Tok Jembal and Bandar Kuala Nerus, which experienced higher burn intensities, likely lost more organic matter and plant cover, altering the thermal and hydraulic dynamics of the soil, consistent with studies [24], [25].

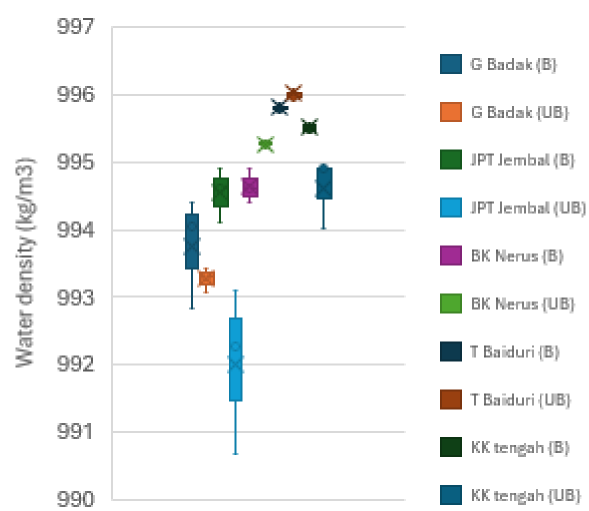


Figure 1 Water density for after (B) and before wildfire (UB) incident. Note: B is burnt, UB is unburnt. G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah

Figure 1 visualizes boxplot on the distribution of water density between burnt and unburnt soils. Gong Badak both soils display approximately near mean with overlapping ranges, and it was consistent with t-test result indicating no significant difference between the burnt and unburnt soils. The other sites (Jalan Pantai Tok Jembal, Bandar Kuala Nerus, Taman Baiduri, Kampung Kuala Tengah) showed its means and variability without any obvious interlap between burnt and unburnt soils, which correspond to significant t-test results indicating a dominant effect of wildfire.

Table 2 P-value from t-test comparing after (burnt) and before (unburnt) wildfire on eight soil related parameters at five sites

Parameters	Location				
	G Badak	JPT Jembal	BK Nerus	T Baiduri	KK tengah
S. Cohesion	-	-	0.039	-	-
Bulk EC	0.016	-	-	-	-
SOM	-	-	0.044	-	-
K_{sat}	-	-	0.035	-	-
ρ_w	-	0.028	0.012	0.011	0.043
Wet ρ_b	0.010	-	-	-	-
Dry ρ_b	0.010	-	-	-	-
Φ	0.010	-	-	-	-

Note: G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah. S. Cohesion is soil cohesion, Bulk EC is bulk electric conductivity, SOM is soil organic matter, K_{sat} is saturated hydraulic conductivity, ρ_w is water density, Wet ρ_b is wet soil bulk density, Dry ρ_b is dry soil bulk density, and Φ is soil porosity. '-' means it is greater than 0.05 in p-value.

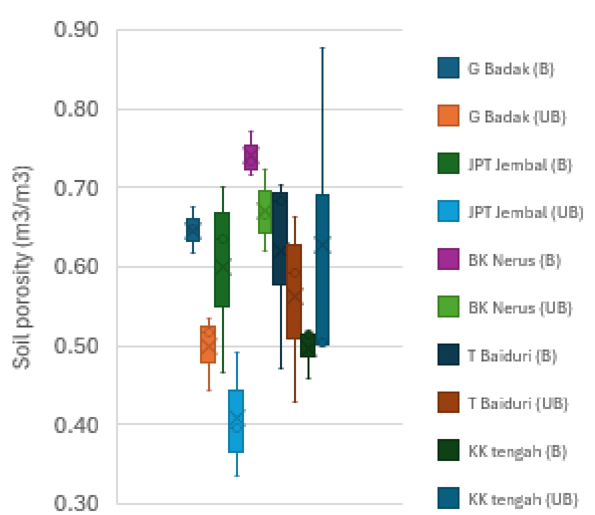


Figure 2 Soil porosity for after (B) and before wildfire (UB) incident. Note: B is burnt, UB is unburnt. G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah

Soil porosity at Gong Badak was found p-value less than 0.05, which demonstrates wildfire has significant impact on soil porosity (refer Table 2). Similarly, in Figure 2, the mean and variability range of both burnt and unburnt soils at Gong Badak were shown to be widely apart. Whereas overlaps were noticed at the other sites (Jalan Pantai Tok Jembal, Bandar Kuala Nerus, Taman Baiduri, Kampung Kuala Tengah). Overall, wildfire tends to increase soil porosity that contradict with that from the literature [2] that normally observed decline in porosity after fire. However, current sites were mainly sandy, not too far from coastal area, hence, we assumed that the initial unburnt sandy soil aggregation tend to occur at greater bulk density, which was expected to disperse after wildfire to result in greater soil porosity. In the Korean red pine forest (sandy loam soil), the study reported lower post-fire bulk density (higher porosity) in surface soils compared to unburned areas, attributed to fine ash infiltrating and loosening the sandy topsoil, which supports the present study's observation of increased soil porosity following wildfire [26].

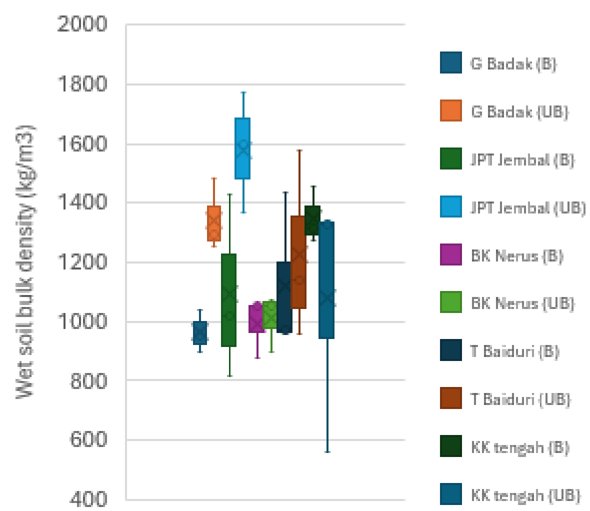


Figure 3 Soil wet bulk density for after (B) and before wildfire (UB) incident. Note: B is burnt, UB is unburnt. G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah

Like the soil porosity, wet bulk density at Gong Badak was found p-value less than 0.05, which demonstrates wildfire has significant impact on soil wet bulk density, as in Table 2. In Figure 3, the mean and variability range of both burnt and unburnt soils at Gong Badak again were shown to be widely apart. Moreover, overlaps of soil wet bulk density values were observed at the other sites (Jalan Pantai Tok Jembal, Bandar Kuala Nerus, Taman Baiduri, Kampung Kuala Tengah). Thus, wildfire tends to decrease the soil wet bulk density similar to those reported in the literature [27], which can be attributed by few possible factors. For instance, the reduction in soil moisture content, and soil structure disruption leading to increase soil porosity. In line with the observation, the soil dry bulk density in Figure 4 shows the soil density by excluding the presence of water was seen to agree to that of the soil wet bulk density, except a slight lower dry bulk density for burnt soil was observed at Bandar Kuala Nerus and Taman Baiduri. While immediate reason for this observation is unclear, it does suggest the possibility of the soils at both locations the capability of holding more soil moisture after the occurrence of wildfire incident.

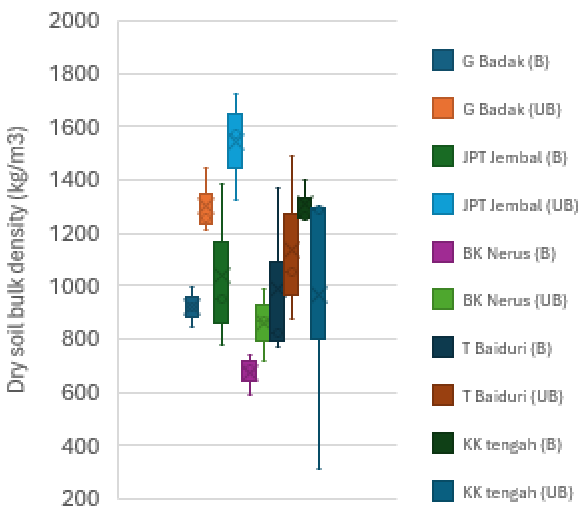


Figure 4 Soil dry bulk density for after (B) and before wildfire (UB) incident. Note: B is burnt, UB is unburnt. G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah

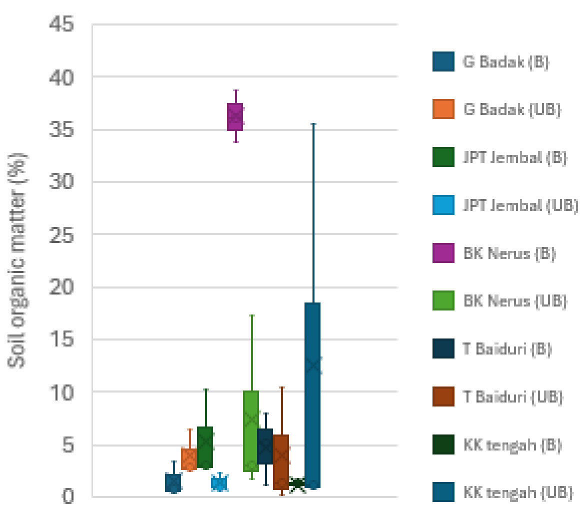


Figure 5 Soil organic matter for after (B) and before wildfire (UB) incident. Note: B is burnt, UB is unburnt. G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah

For soil organic matter (SOM), Bandar Kuala Nerus consistently shows significant differences that its soil organic matter of burnt soil had significant value difference than that before burning. Refer to Figure 5. Indeed, Table 2 indicates Bandar Kuala Nerus has a p-value 0.044 (<0.05), which indicates wildfire influences the SOM of the sites. Similarly in other studies, wildfires consistently reduce soil organic matter (SOM) and carbon pools, with soil organic matter dropping by about 3.7–22.9% on average after fire [28]. Sites like Jalan Pantai Tok Jembal, Bandar Kuala Nerus, and Taman Baiduri appeared to have higher burnt soil organic matter average value than unburnt soils, though the effect of burning on the sites were found to be insignificant (p>0.05). The higher organic matter in burnt soils at the sites could result from partially combusted plant litter, consistent with findings in low-intensity fire zones [29].

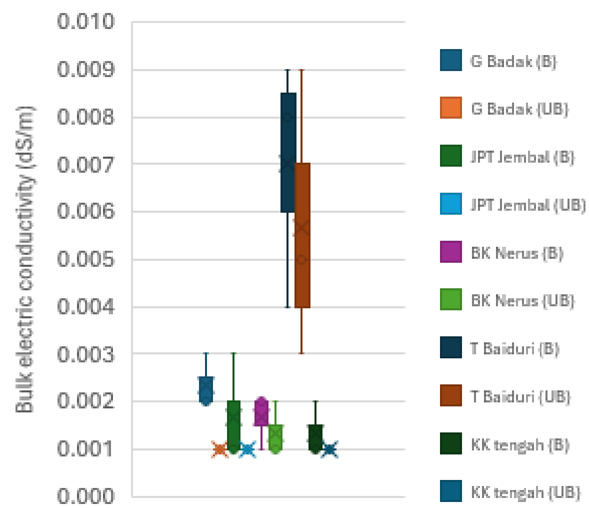


Figure 6 Soil bulk electric conductivity for after (B) and before wildfire (UB) incident. Note: B is burnt, UB is unburnt. G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah

Burnt soil has been reported to have increase soil bulk electric conductivity [30]. The current study found only Gong Badak shows a significant difference (p<0.05), implying site specific factors such as burning intensity could be influencing the soil bulk electric conductivity. Refer to Table 2. The other sites do not exhibit statistically significant differences, suggesting burning may not universally affect soil bulk electric conductivity or that local conditions may buffer the impact. Even though Taman Baiduri appears to have greater soil bulk electric conductivity than other sites, refer to Figure 6, the non-saline soil was normally reported as less than 2 dS/m [31] [32] and also fall within the range of 0.0051-0.13 dS/m for sandy beach ridges in the Kelantan-Terengganu plains [9].

For soil cohesion, only Bandar Kuala Nerus shows a statistically significant difference in soil cohesion between burnt and unburnt soils (Table 2). This is due to the burnt and unburnt conditions having very different distributions (Figure 7). In addition, at Gong Badak and Jalan Pantai Tok Jembal showed larger cohesion in the unburnt condition, but the difference was not statistically significant. Furthermore, all other locations (Taman Baiduri, and Kampung Kuala Tengah) show no significant difference in soil cohesion between the two conditions. Moreover, Taman Baiduri and Kg Kuala Tengah exhibit little to no difference between the burnt and unburnt conditions.

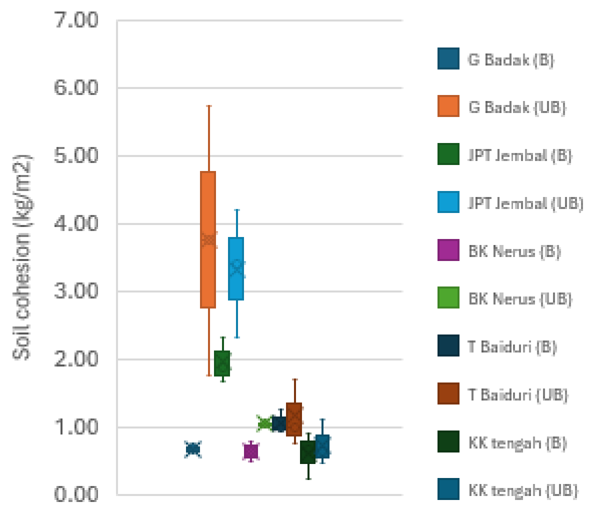


Figure 7 Soil cohesion for after (B) and before wildfire (UB) incident. Note: B is burnt, UB is unburnt. G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah

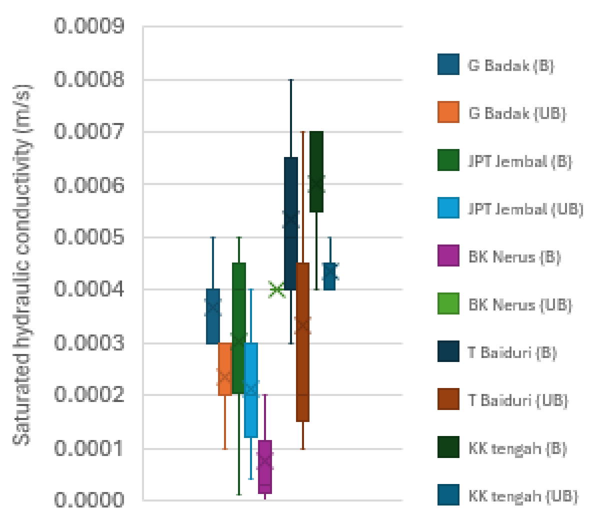


Figure 8 Soil saturated hydraulic conductivity for after (B) and before wildfire (UB) incident. Note: B is burnt, UB is unburnt. G Badak is Gong Badak, JPT Jembal is Jalan Pantai Tok Jembal, BK Nerus is Bandar Kuala Nerus, T Baiduri is Taman Baiduri, and KK Tengah is Kampung Kuala Tengah

Bandar Kuala Nerus is the only site where burning significantly reduced saturated hydraulic conductivity. Refer to Table 2 and Figure 8. The other sites do not show any statistically significant differences. Variability in conductivity differs across sites, suggesting unknown local soil conditions may play a role in how burning affects infiltration and hydraulic properties [33], [34], [35], [36]. However, intense forest fires commonly induce soil hydrophobicity that greatly reduces infiltration rates [4].

4.0 CONCLUSION

This research evaluated the impact of wildfire on several soil physical parameters at five coastal sites in Terengganu, Malaysia. The results indicated that wildfire substantially affected various parameters, such as soil cohesion, bulk electricity, saturated hydraulic conductivity, water density, porosity, bulk density, and organic matter content, with variations dependent on the site. Bandar Kuala Nerus demonstrated substantial alterations in soil cohesion, saturated hydraulic conductivity, and organic matter, while Gong Badak revealed variations in bulk electric conductivity, porosity, and bulk density. These alterations are likely attributable to the degradation of vegetative cover and the thermal modification of soil structure following the fire. Notably, several charred soils had increased porosity, challenging conventional post-fire patterns, potentially attributable to their sandy composition. The effects of wildfires on soil qualities were inconsistent, contingent upon local soil features and fire intensity, underscoring the necessity for tailored soil management measures in post-wildfire environments.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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