

Development of a Fire-Resilient Soil Amendment for Enhancing Post-Wildfire Soil Recovery, Nutrient Retention, and Plant Growth

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ABSTRACT

Wildfires are increasingly frequent and severe disturbances that can degrade soil structure, alter hydrological behaviour, modify nutrient availability, and delay vegetation recovery. This study investigated the effects of controlled thermal exposure on the physical, chemical, and biological properties of four contrasting soil materials—clay, sand, peat moss, and vermiculite—with loamy soil used as a reference. Hydraulic behaviour was assessed using drainage time, filtrate volume, and calculated water retention. Changes in pH and the qualitative availability of nitrogen (N), phosphorus (P), and potassium (K) were evaluated using soil-testing kits. Green gram (*Vigna radiata*) was used as a biological indicator of post-fire plant establishment. Based on the comparative performance of individual components, two composite formulations were developed. Solution 2, comprising 30% clay, 30% vermiculite, 25% sand, and 15% peat moss, demonstrated the most favourable overall performance, particularly in plant growth and nutrient retention after thermal exposure, whereas Solution 1 showed slightly better hydrological performance. These findings indicate that combining soil components with complementary water-management, nutrient-retention, and biological properties may improve post-wildfire soil resilience. The proposed formulation represents a laboratory-scale proof of concept for post-fire restoration; field validation and quantitative chemical and physical characterization are required before practical deployment.

Keywords: Wildfire; Fire-resilient soil; Soil hydrology; Nutrient retention; Plant growth; Soil pH; NPK; Ecosystem restoration; Sustainable land management

1. Introduction

Wildfires are among the most important disturbances affecting terrestrial ecosystems. Although fire is a natural ecological process in many landscapes, increasing temperatures, prolonged drought, climate variability, and anthropogenic land-use pressures have contributed to more frequent and severe fire events. Beyond direct vegetation loss, wildfire can substantially alter soil properties that regulate water movement, nutrient cycling, microbial activity, and vegetation establishment (Kumar et al., 2025).

Healthy soil provides physical support for plants and functions as a reservoir and exchange medium for water and nutrients. Fire can destroy or transform soil organic matter, modify soil aggregation and porosity, alter pH, affect nutrient forms and availability, and reduce biological activity. Removal of vegetation and surface organic cover can additionally increase exposure to runoff and erosion. Consequently, fire-affected soils may experience changes in infiltration and drainage, reduced water retention, nutrient redistribution or loss, and delayed plant recovery (Haas et al., 2026).

The response of soil to fire is not uniform. Soil texture, organic-matter content, mineral composition, moisture status, and heating intensity can influence the magnitude and direction of post-fire changes. A restoration material designed for fire-affected land should therefore ideally combine properties that promote water retention, controlled drainage, nutrient conservation, and plant establishment rather than relying on a single soil component (Santín et al., 2016).

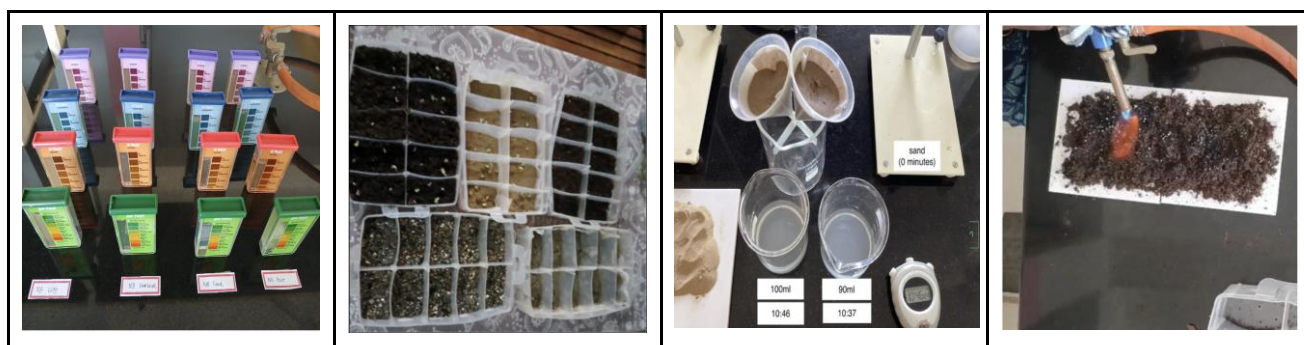
Several approaches have been proposed for reducing fire-related soil degradation, including organic mulches, biochar-based materials, and fire-retardant formulations. However, these approaches can have limitations related to persistence, cost, nutrient balance, or possible environmental effects. An alternative strategy is to develop a composite soil amendment in which different materials provide complementary functions (Bednik et al., 2023).

The present study therefore examined the responses of clay, sand, peat moss, and vermiculite to controlled thermal exposure. Loamy soil was included as a reference material. The study evaluated soil hydrology, pH, qualitative NPK status, and green gram seedling growth. On the basis of these observations, two composite soil formulations were prepared and compared to identify a formulation with improved resistance to fire-induced degradation and greater potential to support post-fire plant recovery.

2. Materials and Methods

2.1 Materials

The study used clay, sand, peat moss, vermiculite, and loamy soil. Loamy soil served as the reference. Bunsen burners were used to provide controlled thermal exposure. Distilled water was used for hydrological and chemical tests to minimize interference from external dissolved minerals. Commercial soil-testing kits containing pH and NPK test reagents were used for qualitative chemical assessment. Standard laboratory equipment, including weighing balances, beakers, funnels, filter papers, burettes, droppers, glass rods, timers, and syringes, was used throughout the experiments.



2.2 Experimental design

Three experimental components were used: (i) soil hydrology, (ii) green gram growth following different heating durations, and (iii) soil pH and qualitative NPK assessment. For hydrology and chemical analysis, unheated soil was compared with soil subjected to 10 min of controlled heating. Plant-growth experiments used heating durations of 0, 5, 10, 15, and 20 min. Unless otherwise stated, replicate measurements were performed and averages were calculated. The experimental draft used an acceptance criterion of $\pm 5\%$ of the average value to assess consistency.



2.3 Soil hydrology

For each soil type, 50 g of soil was placed in a filter funnel containing filter paper. A total of 100 mL of distilled water was passed through the sample. The time required for drainage to cease and the volume of filtrate collected were recorded. Water retained by the sample was estimated as the difference between the volume added and the volume collected. The procedure was performed for unheated soil and for soil heated for 10 min using two Bunsen burners. Three trials were recorded for each treatment.

2.4 Plant-growth assay

Green gram (*Vigna radiata*) seeds were used to evaluate the biological performance of the soil substrates. For each treatment, 50 g of soil was exposed to the designated heating duration (0, 5, 10, 15, or 20 min). Five seeds were placed in each substrate compartment and covered with soil. Twenty millilitres of water were added to each treatment. Seedling height was recorded after one week. The same procedure was applied to the individual soil types and the two composite formulations, with loamy soil serving as the reference.

2.5 pH and NPK assessment

For chemical analysis, 40 g of each soil sample was mixed with 200 mL of distilled water and allowed to settle overnight. The aqueous phase was filtered and used for pH and NPK testing according to the instructions supplied with the soil-testing kit. Unheated and 10-min heated samples were compared. Results were recorded using the qualitative categories provided by the kit: depleted, deficient, adequate, sufficient, and surplus.

3. Results

3.1 Soil hydrology

Thermal exposure altered the drainage behaviour of the soils. The average filtrate volumes and drainage times obtained before and after heating are presented in Tables 1 and 2. In general, heating changed the time required for water to pass through the soil, with several materials showing faster drainage after exposure. Peat moss showed one of the strongest responses, particularly in drainage time and water retention. Vermiculite showed comparatively smaller changes among the individual soil materials.

Table 1. Hydrological characteristics of unheated soils and composite formulations.

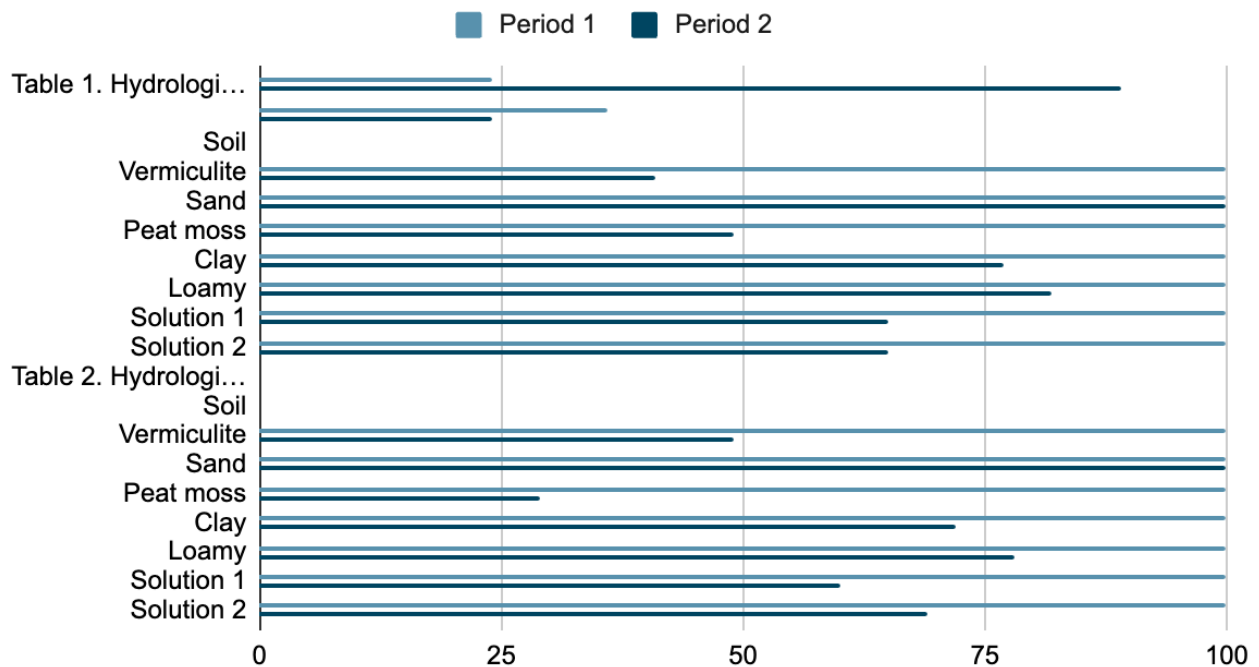
Soil	Water added (mL)	Filtrate T1 (mL)	Filtrate T2 (mL)	Filtrate T3 (mL)	Average filtrate (mL)	Drainage time average (s)
Vermiculite	100	41	45	43	43	146
Sand	100	100	90	95	95	641
Peat moss	100	49	46	47	47.33	1205.33
Clay	100	77	77	77	77	1070.67
Loamy	100	82	81	80	81	174.67
Solution 1	100	65	69	68	67.33	247.67
Solution 2	100	65	45	50	53.33*	1000

Table 2. Hydrological characteristics after 10 min thermal exposure.

Soil	Water added (mL)	Filtrate T1 (mL)	Filtrate T2 (mL)	Filtrate T3 (mL)	Average filtrate (mL)	Drainage time average (s)
Vermiculite	100	49	51	50	50	275
Sand	100	100	100	100	100	384.33
Peat moss	100	29	23	27	26.33	148.67
Clay	100	72	66	70	69.33	557.33
Loamy	100	78	74	76	76	158
Solution 1	100	60	65	66	63.67	221
Solution 2	100	69	64	61	64.77	186.77

The original draft reported that 14 of 16 unheated measurements and approximately 86% of the burnt-soil measurements fell within the stated $\pm 5\%$ accuracy criterion. Greater variability was observed in some peat moss and vermiculite measurements after heating, indicating that these materials may be more sensitive to experimental variation.

Soil Hydrology



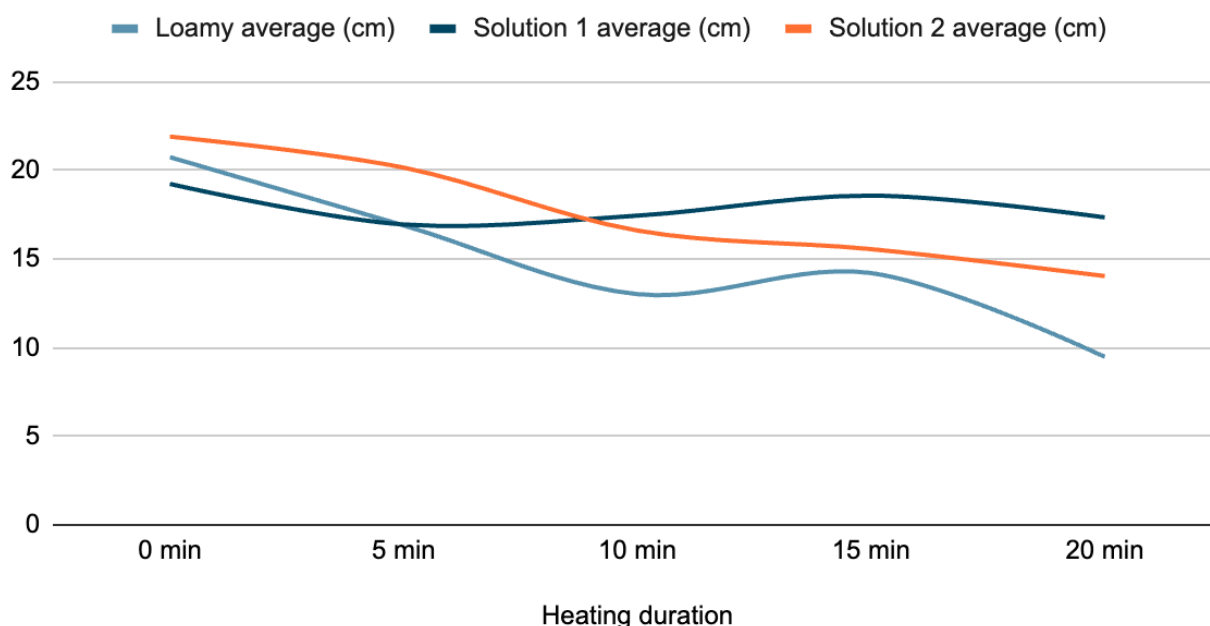
3.2 Effect of heating duration on plant growth

Seedling height after one week varied with both soil type and heating duration. In the individual soils, plant growth generally declined with increasing thermal exposure, with the lowest values frequently occurring after 15–20 min of heating. The composite formulations maintained comparatively favourable growth following thermal exposure. Across the composite treatments, Solution 2 produced the strongest overall plant-growth performance and was more consistent than the individual soil systems.

Table 3. Mean seedling height after one week for loamy soil and the two composite formulations.

Heating duration	Loamy average (cm)	Solution 1 average (cm)	Solution 2 average (cm)
0 min	20.75	19.24	21.91
5 min	16.90	16.95	20.16
10 min	13.02	17.45	16.61
15 min	14.21	18.58	15.56
20 min	9.48	17.35	14.04

Loamy average (cm), Solution 1 average (cm) and Solution 2 average (cm)



The original dataset showed considerable variation between biological replicates. The draft therefore notes that most plant-growth measurements did not fall within the $\pm 5\%$ accuracy range. This variability may reflect differences in seed germination, microenvironmental conditions, substrate heterogeneity, or other uncontrolled biological factors and should be considered when interpreting the growth response.

3.3 pH and nutrient availability

Thermal exposure produced changes in soil pH and qualitative nutrient status. Vermiculite and sand increased from pH 7.0 to below 7.5, clay increased from pH 6.5 to below 7.5, and loamy soil increased from pH 6.0 to 6.5. Peat moss decreased from pH 6.5 to 6.0 and therefore remained closest to the target pH of 6 after heating.

Table 4. Qualitative pH and NPK status before and after thermal exposure.

Soil	N before	N after 10 min	P before	P after 10 min	K before	K after 10 min
Vermiculite	Adequate	Adequate	Deficient	Deficient	Depleted	Deficient
Sand	Deficient	Adequate	Adequate	Adequate	Depleted	Deficient
Peat moss	Sufficient	Sufficient	Adequate	Adequate	Depleted	Deficient
Clay	Deficient	Adequate	Adequate	Adequate	Depleted	Depleted
Loamy	Surplus	Surplus	Sufficient	Sufficient	Depleted	Depleted

The composite formulations also showed different nutrient responses. Solution 1 retained sufficient nitrogen and adequate potassium, while phosphorus remained deficient. Solution 2 retained adequate nitrogen; potassium remained deficient, while phosphorus changed from adequate to deficient. Based on the combined observations, the original study identified Solution 2 as having the better overall post-fire nutrient-retention and plant-growth performance.

4. Discussion

Wildfire-induced thermal stress can alter several interconnected soil functions, and the present results demonstrate that these responses vary among soil materials. The hydrological, chemical, and biological measurements collectively indicate that soil resilience cannot be evaluated using a single parameter.

Thermal exposure changed drainage behaviour in the tested soils. Faster passage of water after heating may indicate modification of pore structure, aggregation, or water-repellent characteristics. However, faster drainage should not automatically be interpreted as improved soil quality. If water passes rapidly through the soil without adequate retention, plant-available

water may decline and the risk of nutrient leaching and erosion may increase. A restoration substrate should therefore maintain a balance between infiltration, drainage, and water retention. Peat moss showed a pronounced response to heating in the hydrological experiment, whereas vermiculite showed comparatively lower sensitivity. These contrasting behaviours illustrate the value of combining materials with different physical characteristics. Sand contributes drainage, clay can increase water and nutrient retention, vermiculite can contribute moisture management and aeration, and peat moss contributes organic matter and supports plant establishment. The plant-growth experiment provided a biological measure of whether the physical and chemical properties of the substrates were sufficient to support early recovery. Increasing heating duration generally reduced plant height in the individual soil systems, particularly at longer exposure durations. This pattern is consistent with the interpretation that prolonged thermal exposure can impair soil functionality and plant establishment. However, the response was not perfectly linear across every treatment, and the relatively high variability among biological replicates indicates that factors other than thermal exposure also influenced seedling development.

The composite formulations performed comparatively well in the plant-growth assay. Solution 2 showed the strongest overall performance, particularly when the objective was to maintain plant establishment following thermal exposure. This is important because restoration success depends ultimately on the capacity of a post-fire substrate to support vegetation rather than only on short-term changes in drainage or nutrient-test categories.

Changes in pH were also observed following heating. Most materials shifted towards higher pH, whereas peat moss decreased to pH 6.0. An increase in pH following burning may be associated with the presence or release of alkaline mineral constituents in ash. Such a shift can influence nutrient solubility and plant nutrient uptake. The fact that peat moss remained closest to the target pH highlights its potential contribution to balancing the chemical environment of a composite formulation.

Nitrogen showed improvements from deficient to adequate status in sand and clay after heating, while vermiculite and peat moss retained their respective categories. This may reflect short-term changes in nutrient form or mineralization. Nevertheless, increased post-fire availability should not be equated with long-term nutrient conservation because nutrient losses can occur through volatilization, runoff, and erosion under more severe or prolonged fire conditions.

Phosphorus showed relatively limited qualitative change in the individual soil samples, whereas potassium improved from depleted to deficient status in several treatments. The potassium response may be associated with nutrient release from mineral or ash-derived material. Because the study used qualitative soil-testing kits, these results should be interpreted as relative categories rather than precise measurements of nutrient concentration.

The comparison of the two composite formulations reveals a useful functional trade-off. Solution 1 showed slightly better hydrological behaviour after burning, whereas Solution 2 provided stronger plant growth and was identified as the better overall formulation for post-fire performance. This distinction is important for amendment design because restoration requires simultaneous management of water, nutrients, and biological establishment.

Solution 2 contained 30% clay, 30% vermiculite, 25% sand, and 15% peat moss. Its performance suggests that integrating materials with complementary characteristics can provide greater functional resilience than relying on an individual substrate. The formulation therefore represents a promising laboratory-scale candidate for post-wildfire soil restoration.

At the same time, the experimental design has limitations. The wildfire was simulated by heating soil with Bunsen burners rather than reproducing the complex temperature gradients, heating duration, ash deposition, smoke chemistry, and moisture conditions of a natural wildfire. In addition, the NPK measurements were qualitative and the plant-growth data showed substantial biological variability. Future investigations should therefore include controlled temperature measurements, larger sample sizes, quantitative nutrient analysis, soil organic carbon, microbial activity, aggregate stability, and longer-term vegetation responses.

5. Conclusion

The present study demonstrates that controlled thermal exposure can modify soil hydrology, pH, nutrient availability, and plant-growth performance, with the magnitude of the response depending on soil type. The results indicate that post-wildfire degradation involves interacting physical, chemical, and biological changes and therefore requires an integrated restoration strategy.

Comparison of individual soil components supported the development of two composite formulations. Although Solution 1 showed slightly better hydrological performance, Solution 2 provided superior overall biological performance and favourable nutrient-retention

characteristics following thermal exposure. The optimized formulation consisted of 30% clay, 30% vermiculite, 25% sand, and 15% peat moss.

The results suggest that combining materials with complementary properties can create a more balanced substrate capable of supporting post-fire water management, nutrient availability, and vegetation establishment. Solution 2 can therefore be considered a promising candidate for further development as a fire-resilient soil amendment.

However, the present findings represent a laboratory-scale proof of concept. Field trials are required to determine the performance of the formulation under realistic wildfire and environmental conditions. Future studies should also quantify soil physical properties, nutrient concentrations, carbon dynamics, microbial responses, and longer-term plant establishment. Such validation will be essential before recommending the formulation for large-scale ecological restoration, reforestation, agricultural recovery, or other fire-affected landscapes.

6. Study Limitations and Future Perspectives

The study provides an initial comparative assessment rather than a full field-scale validation. The use of Bunsen burners provides controlled thermal exposure but does not reproduce the complete range of conditions associated with natural wildfires. The qualitative NPK kit provides categorical rather than quantitative nutrient measurements, and the relatively high variability in plant-growth observations limits statistical interpretation. Future work should therefore incorporate controlled temperature monitoring, replicated experiments with larger sample sizes, quantitative soil chemistry, measurements of water-holding capacity and hydraulic conductivity using standardized methods, microbial and soil-carbon analyses, and longer observation periods. Field trials under fire-prone environmental conditions would be particularly important for determining the amendment's practical feasibility, stability, cost-effectiveness, and ecological safety.

7. References

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