Phi: Jurnal Pendidikan Fisika dan Terapan
Vol. 12, No. 2 (2026) 184-192
ISSN: 2460-4348, e-ISSN: 2549-7162
https://jurnal.ar-raniry.ac.id/index.php/jurnalphi/index

Article Type: *orginial research*

Soil Physics Analysis of pH and Water Retention Capacity in Productive Paddy Fields and Soils Degraded by Waste-Burning Residues

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ARTICLE INFO

Article History:
Received: 26 February 2026
Revised: 16 April 2026
Accepted: 19 April 2026
Published: 21 April 2026

Keywords:
Soil physics; Soil pH; Water retention capacity; Porosity; Waste-burning residues; Paddy field soil

ABSTRACT

This study investigated the differences in soil pH and water retention capacity between productive paddy soil and soil degraded by waste combustion residues from a soil physics perspective. The waste combustion soil used was household waste combustion soil containing organic and inorganic waste. Combustion residues can alter the physicochemical properties of the soil, particularly porosity, capillarity, and moisture dynamics, which affect soil water retention behavior. A comparative quantitative approach was used by collecting soil samples at a depth of 0–20 cm from two different locations. Soil pH was measured using a digital pH meter, while water retention capacity was analyzed using standard laboratory procedures. The results showed that the productive paddy soil exhibited a pH close to neutral (6.8), higher porosity, stronger capillary action, and high water retention capacity (90%). In contrast, the degraded soil exhibited alkaline conditions (pH 8.7), reduced pore connectivity, impaired moisture dynamics, and lower water retention capacity (60%). These findings suggest that waste combustion residues negatively impact soil structure and water retention mechanisms. Therefore, appropriate waste management and soil rehabilitation strategies are needed to restore soil function and agricultural productivity.

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1. INTRODUCTION

Soil quality plays a crucial role in sustaining agricultural productivity, particularly in paddy field ecosystems that depend on stable physicochemical conditions. Productive rice fields require balanced soil pH, adequate organic matter, and stable pore distribution to maintain optimal nutrient availability and water retention capacity (Nursyamsi and Supriyo, 2020;Setiawan, 2018) Soil physical characteristics such as porosity and aggregate stability are directly related to moisture dynamics and capillary water movement, which determine crop performance (Kurniawan, 2015;Josua *et al.*, 2019). However, increasing environmental pressure due to improper waste management practices has contributed to soil degradation in agricultural landscapes. Open waste burning, especially at the household level, remains common in many regions of Indonesia and poses serious environmental risks

(Bimastyaji *et al.*, 2023). Several studies have shown that unmanaged waste burning significantly alters soil physicochemical properties, including pH shifts, nutrient imbalance, and reductions in microbial activity (Murniati, 2017; Ullah and Islam, 2019; Verma, Marschner and Seshadri, 2017). Assessment of degraded soils from waste-burning sites indicates measurable declines in soil quality and functionality (Mahendra, 2024; Rahmawati, 2023). Fire-induced soil degradation has also been widely reported in forest and peatland ecosystems. Peat fires in Indonesia, for instance, have caused substantial changes in soil flora, fauna, and soil properties, leading to long-term environmental damage (Basuki, Bambang and Erianto, 2019). Post-fire impacts include increased soil alkalinity, reduced organic matter content, and disruption of aggregate structure (Choi, Choi and Lim, 2021; Febri *et al.*, 2024; Veronika and Ngole-Jeme, 2019).

Similar findings have been reported in comparative studies of burned and unburned land, where soil water retention characteristics changed significantly after fire exposure (Ebel and Mirus, 2025; Wuyep, Rampedi and Ifegbesan, 2020). Soil factors influencing fire behavior and subsequent degradation processes have also been extensively reviewed (Sunny, Mohammad and Zalina, 2025). Combustion residues, including ash particles and alkaline mineral compounds, are known to affect soil pH and nutrient dynamics (Pranata, 2019). In agricultural soils, excessive alkalinity can reduce nutrient solubility and impair crop productivity. Furthermore, structural changes in pore distribution affect capillary forces and water-holding capacity (Wong, Chen and Wong, 2017). Soil water retention behavior is closely related to aggregate stability and organic carbon content, which are crucial for soil moisture retention (Kurniawan, 2015). The biological condition of the soil after a fire event also determines the potential for remediation and recovery (García-Velázquez, 2025; Veronika, Muli and Oktavina, 2024)). Although numerous studies have examined the impacts of fire and waste burning on soil chemical or biological properties separately, studies integrating soil chemical changes with physical mechanisms such as porosity, capillarity, and moisture dynamics in rice paddy ecosystems are limited. Most studies have focused on forest or upland soils, while rice paddy systems, which have distinct hydrological characteristics, remain underexplored. Furthermore, studies directly linking burning residues to changes in soil water retention behavior in productive versus degraded rice paddy soils are scarce. Therefore, this study provides a comprehensive soil physics-based evaluation of soil degradation caused by burning residues in rice paddies. By integrating pH analysis, porosity assessment, and water retention capacity measurements, this study bridges the gap between soil chemical changes and physical moisture regulation mechanisms. While pH is integrated as an essential indicator of soil chemical quality, it is not positioned as the primary causal factor for changes in physical structure. Instead, both aspects undergo simultaneous degradation due to exposure to burning residues. The composition of ash and alkaline minerals in the residue acts in a dual manner, distorting the ionic balance (alkalinity) and mechanically clogging micropores and destabilizing organic aggregates. Thus, the decrease in water retention capacity is a consequence of the transformation of the physical structure and the reduction in effective porosity, while pH fluctuations serve as a sensitive parameter indicating the presence of these pollutants. These findings contribute to a deeper understanding of how combustion residues affect soil structure and agricultural sustainability, particularly in rice-based ecosystems.

2. METHOD

2.1 Research Types and Designs

This quantitative study uses a comparative design to compare the physical and chemical properties of soil, namely acidity (pH) and water retention capacity, on two different land types. The research subjects included productive rice paddy soil and soil degraded by waste burning residue. A comparative approach was used to highlight differences in soil characteristics resulting from waste burning activities.

2.2 Research Location and Time

Soil samples were collected from two locations in Hamlet VII A, Karang Anyar, Beringin Village: (1) 3°36'50.4"N 98°53'56.5"E a productive paddy field and (2) 3°36'47.5"N 98°53'55.8"E land exposed to waste-burning residues. Samples were taken from the topsoil layer (0–20 cm), representing the active root zone and the most sensitive layer to environmental changes. Each soil type was collected in five replications. For pH measurement, soil samples were prepared using a soil–water suspension at a ratio of 1:3.5 (w/v).

2.3 Sampling Techniques

Soil sampling was conducted using a purposive sampling technique, taking into account the characteristics of the land representing productive rice fields and degraded land due to waste burning. When researchers wanted to take soil samples, researchers considered productive rice fields and also irrigated rice fields that receive a regular water supply without the need for external water supplies to meet the needs of the rice fields. Researchers took rice field soil to be sampled at a depth of (0-20 cm). In addition, researchers also took soil from burned household waste (organic and non-organic) as research samples, researchers also considered taking this soil sample, researchers took burnt soil where waste burning often occurs on the land, and the soil was also taken at a depth of (0-20 cm). Each soil sample that researchers have obtained will be dried naturally, cleaned of plant debris and foreign objects, then homogenized before testing. The collected soil samples were air-dried, cleaned of plant debris and foreign objects, and homogenized before laboratory analysis.

2.4 Experimental Procedure

The experimental setup used for soil preparation, pH measurement, and water retention testing is shown in Figure 1. The apparatus included soil containers, measuring cylinders, a paper pH meter, filter materials, and supporting laboratory instruments.



Figure 1. Experimental setup for soil sampling and laboratory measurements, including soil containers, measuring instruments, and water retention testing apparatus.

Soil pH was measured using a standard soil–water suspension method. Soil samples were mixed with distilled water at a fixed ratio and stirred until homogeneous. The pH value was determined using a calibrated paper pH meter after the suspension reached equilibrium. The visual comparison of soil characteristics and pH testing procedure is presented in Figure 2.



Figure 2. Soil pH measurement and visual comparison between productive paddy soil and degraded soil affected by waste-burning residues.

Water retention capacity was measured using a gravimetric approach. A total of 100 mL of distilled water was poured into each soil sample placed in a perforated container lined with filter material. After gravitational drainage stabilized, the drained water volume was recorded. Water retention percentage was calculated using Equation (1):

$$\text{Water Retention (\%)} = \frac{V_{outset} - V_{droplets}}{V_{outset}} \times 100\% \quad (1)$$

Where V_{outset} is the initial water volume applied to the soil and $V_{droplets}$ is the drained water volume. This method reflects soil moisture dynamics influenced by pore distribution, capillary forces, and structural conditions.

2.5 Data Analysis

All measurements were conducted in five replications. Data were analyzed descriptively and statistically using an independent sample t-test to determine significant differences between productive and degraded soils. The results were presented in tables and graphical forms

3. RESULTS AND DISCUSSION

The analysis revealed significant differences in soil physicochemical properties between productive paddy soils and soils degraded by waste-burning residues. The observed parameters included soil pH, water retention capacity, and porosity, which represent both chemical and physical characteristics of soil.

3.1 Soil pH Characteristics

The findings indicate a distinct difference in soil pH between the two soil types. Productive paddy soil had an average pH of 6.8, which is within the ideal range for nutrient availability and plant growth. In contrast, the degraded soil exhibited a higher average pH of 8.7, reflecting alkaline conditions. This increase is likely influenced by combustion residues containing alkaline minerals and ash, which disrupt the soil's chemical balance and decrease nutrient solubility.

Figure 3. Comparison of soil pH between productive paddy soil and degraded soil influenced by waste-burning residues.

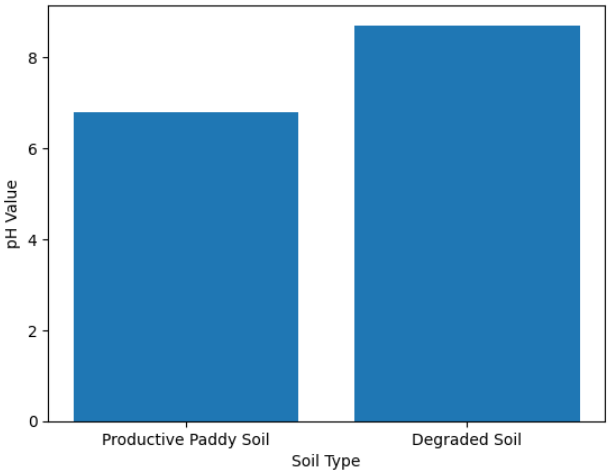


Figure 3. Comparison of soil pH between productive paddy soil and degraded soil affected by waste-burning residues, Error bars represent standard deviation (n = 5)

The alkaline condition in degraded soils indicates chemical alteration due to combustion activities. High pH levels may reduce nutrient availability, particularly phosphorus and micronutrients, thereby affecting soil fertility and plant productivity.

3.2 Water Retention Capacity

Productive paddy soils demonstrated a significantly higher water retention capacity compared to degraded soils. The average water retention in productive soil reached 90%, while degraded soil retained only 60% of water. This difference reflects variations in soil structure, organic matter content, and pore distribution.

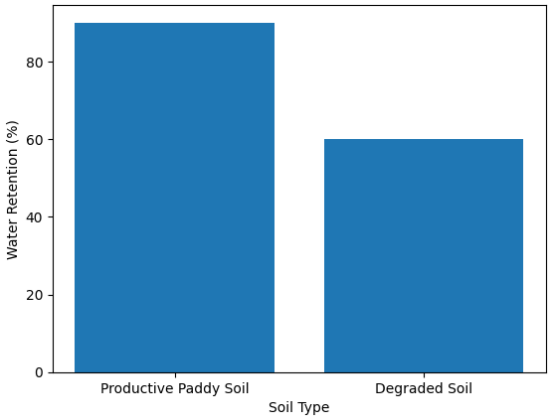


Figure 4. Comparison of water retention capacity between productive and degraded soils, Error bars represent standard deviation (n = 5)

The reduced ability of degraded soils to retain water indicates structural damage caused by combustion residues. Loss of organic matter and aggregate stability leads to weaker capillary forces and faster gravitational drainage. As a result, degraded soils are less capable of maintaining soil moisture for plant growth.

3.3 Soil Porosity

Porosity analysis revealed notable differences between productive and degraded soils. Productive soil exhibited higher porosity with an average value of 51.6%, whereas degraded soil

showed lower porosity at approximately 37%. These findings indicate that waste-burning residues significantly affect soil pore distribution and connectivity.

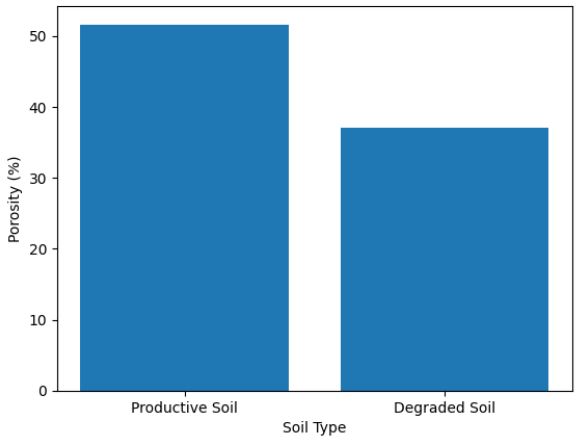


Figure 5. Soil porosity in productive paddy soil and degraded soil affected by waste-burning residues, Error bars represent standard deviation (n = 5)

Higher porosity in productive soil supports stronger capillary action and better moisture storage, allowing water to be retained within micro-pores. Conversely, degraded soil is dominated by larger pores, which accelerate water loss and reduce moisture retention capacity.

3.4 Soil Physics Interpretation

From a soil physics standpoint, variations in pH, water retention, and porosity are closely linked through shifts in soil structure and pore system behavior. Residues from combustion impact the soil by diminishing organic matter content and weakening aggregate stability, which subsequently alters pore size distribution and disrupts the balance between macropores and micropores. These structural changes reduce the volume and connectivity of micropores, which play a critical role in retaining water and supporting capillary action. As a result, the movement of water and air in the soil becomes less controlled. In degraded soils, the prevalence of macropores promotes rapid gravitational drainage, while the decline in micropores diminishes the capillary forces needed to hold moisture. Based on capillarity principles, finer pores produce stronger capillary forces that improve water retention, whereas larger pores mainly enable quick drainage. This explains why degraded soils tend to have lower water retention capacity and less stable moisture dynamics compared to more fertile soils.

Productive soils, on the other hand, maintain stable pore connectivity and aggregate formation, enabling efficient water storage and distribution. The presence of well-structured aggregates supports a balanced pore system, allowing optimal interaction between capillary forces and gravitational flow. This condition is essential for sustaining soil moisture availability in paddy field systems, which rely heavily on stable hydrological conditions.

In addition to physical changes, the increase in soil pH observed in degraded soils reflects the accumulation of alkaline mineral compounds derived from combustion residues. Although pH is not a direct driver of physical structural changes, it serves as an important indicator of chemical alteration associated with ash deposition and nutrient imbalance. The simultaneous occurrence of chemical and physical degradation suggests that combustion residues affect soil systems in an integrated manner.

These findings are consistent with previous studies. (Certini, 2021), (Bodí, 2020), and (Mataix-Solera, 2022). reported that burning processes increase soil pH while decreasing aggregate stability, porosity, and water retention capacity. More recent studies have further demonstrated that combustion residues can clog micropores, disrupt pore continuity, and weaken capillary forces,

ultimately reducing soil functionality and moisture regulation (Ebel and Mirus, 2025; García-Velázquez, 2025)

Compared to previous research, this study provides additional insight by explicitly linking chemical indicators such as pH with physical mechanisms including pore distribution and capillary behavior in paddy field ecosystems. While many earlier studies focused on forest or upland soils, this research highlights that similar degradation mechanisms also occur in irrigated rice fields, where water retention and pore stability are critical for agricultural productivity.

Overall, the results confirm that waste-burning residues induce systematic physicochemical degradation. Structural damage to the pore system plays a dominant role in reducing water retention capacity, while pH acts as a supporting indicator of chemical disturbance. This integrated understanding strengthens the interpretation of soil degradation processes and emphasizes the importance of sustainable waste management in maintaining soil quality.

3.5 Statistical Analysis

Statistical analysis using an independent sample t-test revealed highly significant differences between productive and degraded soils for all observed parameters ($p < 0.001$). The test results showed strong statistical separation, with large t-values and consistent degrees of freedom ($df = 8$), indicating robust differences between the two groups.

In addition, effect size analysis indicated a strong magnitude of difference between the two soil types, confirming that the observed variations are not only statistically significant but also practically meaningful. These results demonstrate that waste-burning residues have a substantial impact on soil physicochemical properties.

4. CONCLUSION

This study demonstrates significant differences in the physicochemical properties of soil between productive paddy fields and soils degraded by waste-burning residues. Productive soils showed near-neutral pH, higher porosity, and better water retention capacity, reflecting stable soil structure and optimal moisture dynamics. In contrast, degraded soils exhibited more alkaline conditions, reduced pore distribution, weakened capillary behavior, and much lower water-holding capacity.

Statistical analysis confirmed that the differences in pH, porosity, and water retention were highly significant ($p < 0.001$), indicating that combustion residues substantially alter both chemical and physical soil properties and reduce agricultural sustainability. These findings emphasize the importance of pore connectivity, capillary forces, and moisture regulation in maintaining soil productivity. Therefore, further research is recommended to evaluate the use of biochar as a rehabilitation strategy, as it has strong potential to improve aggregate structure, increase porosity, enhance water retention, and restore soil hydrophysical functions for long-term agricultural sustainability.

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