Evaluation of Penetration, Retention and Distribution of Chromated Copper Arsenate in Various Wooden Pole Classes in Mufindi District, Tanzania

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ABSTRACT

This study examined the penetration, retention, and distribution of Chromated Copper Arsenate (CCA) preservatives in four classes of wooden utility poles, namely Light, Medium, Intermediate, and Stout, in Mufindi District, Tanzania. The aim was to evaluate the effectiveness of CCA treatment in improving pole durability and service life. Poles were pressure-treated, with preservative penetration measured using a graduated plate and retention assessed with an ED-XRF analyzer (X-MET8000 Optimum). Results showed significant differences among pole classes in CCA uptake. Light poles had the highest mean retention (25.50 kg/m^3), while medium poles had the lowest, although stout poles demonstrated overall superior retention uniformity. ANOVA confirmed statistically significant variations ($p < 0.05$) in both penetration and retention. A very weak positive correlation ($r = 0.001$) between penetration depth and retention indicated that factors other than penetration influence preservative uptake. Penetration decreased with increasing pole size, from 30.01 mm in light poles to 24.97 mm in stout poles, with a general mean of 27.39 mm. Moisture content was consistent across classes, averaging 25.45%. Variations in penetration and retention were also noted along pole lengths. The findings emphasize the need to tailor treatment protocols to pole size and recommend further research into improved preservative formulations and enhanced treatment methods to ensure long-term durability.

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1.0 Introduction

Worldwide, the wooden utility pole industry plays important roles in generating employment, revenue, industrial development, household income, and forestry by-products. Within East Africa, Tanzania is recognised regionally for having a comparative advantage in producing high-quality wooden poles due to favourable growing conditions, wood markets, and opportunities for value addition. Milledge (2017) reported that the Southern Highlands are the hubs of plantation forestry with remarkable growth in public and private plantations and woodlots, an indicator of long-term investments in a sector that needs to be nurtured.

Wooden poles are crucial in various construction and utility applications, from electrical transmission to telecommunications and fencing. Yet, their vulnerability to decay and deterioration makes effective preservation methods essential for prolonging their service life (Mohebby, 2003; Niemz & Mannes, 2012; Shafieezadeh *et al.*, 2013; Alfieri & Correa, 2018). The chemical preservatives, widely used for this purpose, offer protection against fungal decay, insect infestation, and environmental degradation. The success of preservative treatments hinges on several factors, including the type of preservative, the treatment method, the wood species, and the initial quality of the poles, as observed and reported by Klem (1984), Darrel (1973) and Shafieezadeh *et al.* (2013).

Preservative treatment is the primary strategy to extend the shelf life of wood products, thereby reducing replacement costs and promoting the rational and efficient use of forest resources (Lebow *et al.*, 2004; Freeman & McIntyre, 2008). In Uganda, for example, the demand for preserved utility poles has grown to support the expanding rural electric grid, particularly with Eucalyptus species, which are frequently treated with coal tar creosote and Copper Chrome Arsenate (CCA) preservatives, as reported by Mugabi and Thembo (2018). Penetration, referring to the depth at which preservatives enter the wood structure, is critical in wood preservation. It ensures that preservatives reach the areas most susceptible to insects and wood-decay fungi. This penetration ability depends on various factors, such as wood type, moisture content, porosity, and the formulation of the preservative, as Siau (1984), Lebow (1996), and Kirker and Lebow (2021) have noted.

Penetration refers to the depth to which a preservative enters the wood structure during treatment, influencing how well the inner zones are protected. Retention, on the other hand, represents the amount of preservative chemical that remains in the wood after treatment, measured in kilograms per cubic meter (kg/m^3), which determines the level of protection against decay and insect attack. Regulatory standards and building codes specify minimum retention levels for various applications (Graham & Helsing, 1979; EPA, 2011; EPA, 2015; Mugabi & Thembo, 2018). Distribution complements these two variables by describing how evenly the preservative is spread within the treated wood. A uniform distribution ensures consistent protection throughout the pole, minimising weak points where decay or insect infestations could occur. Uneven distribution, conversely, can result in premature pole failure even when overall retention appears adequate, as described by Mugabi and Thembo (2018). Tropical timber species are highly prized for their diverse colours, chemical makeup, physical and mechanical properties, and long-lasting qualities. They are used to make furniture, utility poles, musical instruments, car interior trims, and handicrafts. The global trade in tropical timber products reached 273.21 million m^3 in 2014, underscoring their importance (JORF, 2004; OIMT, 2015; Ringman, 2017).

Wood preservatives are essential for extending the lifespan of wooden poles used in power transmission and distribution. These preservatives penetrate the wood to prevent decay caused by fungi and insects, but their effectiveness depends on their concentration, penetration, and retention within the wood (Darrel, 1973; Lebow *et al.*, 2004; Groenier & Lebow, 2006; Archer & Lebow, 2006). Copper-based preservatives like Chromated Copper Arsenate (CCA) and creosote are commonly used for treating wooden poles (Kongo *et al.*, 2019).

In Tanzania's Mufindi District, wooden poles are extensively employed in rural electrification projects, agricultural fencing, and other infrastructure developments. Despite their widespread use, there is limited knowledge about the effectiveness of preservative treatments across the different pole grades used in the region. Understanding the extent to which chemical preservatives penetrate, distribute and are retained within various pole classes is vital for optimising the treatment processes of these wooden poles, as discussed by Cookson (2000) and Brischke and Lampen (2014). Assessing the concentration, penetration, and retention of wood preservatives is also important for verifying the effectiveness and longevity of treated wood materials (Mattos *et al.*, 2012; Bossardi & Marques, 2022; Khademibami & Bobadilha, 2022).

This study was conducted to evaluate the penetration, retention, and distribution of chemical preservatives in various wooden pole classes in Mufindi District, Tanzania. Specifically, the study aimed at measuring the penetration and retention of CCA across different classes of wooden poles (light, medium, intermediate, and stout), assessing the distribution of CCA along the poles at different positions (near the ground, mid-point, and top), and exploring the relationship between pole size and the effectiveness of preservative treatments.

Understanding the factors that influence preservative effectiveness enables the wooden pole industry to improve treatment processes, thereby enhancing the durability and service life of utility poles. This study is justified by the urgent need to address premature pole failures; as reported by Milledge (2017), about 10% of wooden poles fail within 10 years despite an expected lifespan of 40 years. The research findings will not only guide improvements in treatment standards and operational practices but also stimulate innovation and technology transfer in developing more effective and sustainable preservation methods. Such advancements could enhance the reliability of power distribution networks in Tanzania. Moreover, the outcomes will benefit government and non-governmental stakeholders, including wood preservation factories, policymakers, researchers, and utility companies, by promoting the rational use of treated poles through evidence-based selection, proper handling, regular inspection, and timely re-treatment.

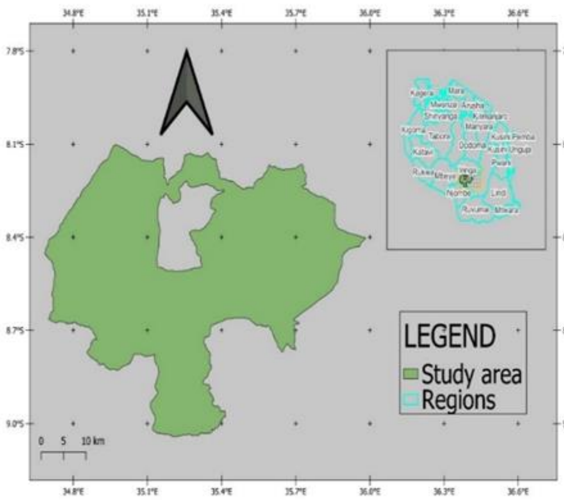
2.0 Materials and Methods

2.1 Study Area

The study was conducted in Mufindi District, which lies between latitude 8° 00′–9° 15′ South and longitude 34° 35′–35° 55′ East (Fig. 1). The district is bordered by Iringa Rural District to the north, the Njombe Region to the south, the Morogoro Region to the east and the Singida Region to the west, with an average elevation of 1879.14 m a.s.l. and covers 7,123 km², which is about 19.9% of the total area of the Iringa Region (NBS, 2013).

Figure 1

A map showing Mufindi District, Iringa Region, Tanzania (Mweta, 2025)



The study area also has various wood preservation plants ranging from small-scale to large-scale Industries (Table1) (Balama, 2022).

Table 1

Various Pole Treatment Plants in Mufindi, Iringa Region, Tanzania

		Ownership	
S/No	Name of Industry	Individual	Group
1	Qwihaya General Enterprises Company Ltd	0	1
2	Sao Hill Industries Ltd (Poles)	0	1
3	Mufindi Wood Poles Plant and Timber Ltd	0	1

4	Shedaffa General Supplies Ltd (Poles)	1	0
5	Leshea Investment Company (Poles)	0	1
6	Mafinga Wood Treatment Plant Ltd	0	1

In Mufindi District, the wet season is overcast, the dry season is windy and mostly clear, and it is hot year-round. Over the year, the temperature typically varies from 15°C to 32°C and is rarely below 10°C or above 34°C. Agriculture is the cornerstone of the district's economy, with the National Agriculture Sample Survey of 2008 highlighting that the agriculture sector ranks first in the sale of both annual and permanent crops (NBS, 2013). The choice of the study area is based on the uniqueness of the district, being the largest producer of utility poles with the ability to supply 131,560 m^3 with an installed capacity of 374,818 m^3 (Balama, 2022). Further, the study focused on *Eucalyptus* species and their clonal hybrids, as these are the most commonly used species for utility poles in Tanzania.

2.2 Study Design

A stratified sampling design was employed in this study, with treated utility poles categorised into strata based on their class: light poles, medium poles, intermediate poles, and stout poles. Within each stratum, 8 poles were randomly selected for analysis, following the methodology adopted by Ssemaganda *et al.* (2011). These poles were further classified according to their categories as specified by the Tanzania Bureau of Standards (TBS) in TZS 686:2021 (TBS 2021a; TBS 2021b).

2.3 Data Collection

2.3.1 Selection of Wooden Poles

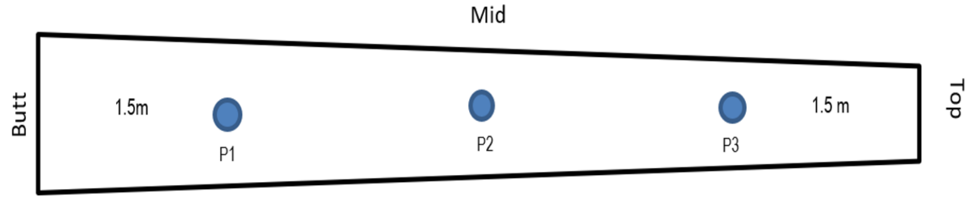
For this study, 96 poles were selected from three different wood preservation industries. There were 24 poles for each pole class. Utility poles are classified into four main classes – Light, Medium, Intermediate, and Stout – based on their length and top diameter, which determine their mechanical strength and suitability for different applications. Light poles (8–10 m, 120–173 mm top diameter) are used for low-load purposes, while medium poles (8–14 m, 140–233 mm) serve standard distribution needs. Intermediate poles (10–14 m, 180–253 mm) are suitable for higher load demands, and stout poles (10–18 m, 200–308 mm) are used in heavy-duty applications such as transmission lines. As the class increases, both the pole length and diameter increase to provide greater strength and durability. The moisture content of the poles was measured using a moisture meter, which was inserted to a depth of 25.4 mm into the wood. The treated poles from three preservation plants were selected for study based on their installed capacities (large supplier, mid supplier and lower supplier as Enterprise 1, Enterprise 2 and Enterprise 3, respectively).

2.3.2 Determination of CCA Penetration

Three wood borings were extracted from each wooden pole (refer to Fig. 2), specifically at 1.5 metres from the butt end (theoretical ground line), at mid-length (50% of the total length), and 1.5 metres from the top end, using an incremental core as described by Mugabi and Thembo (2018). The dimensions of the borings were measured using a digital calliper, with particular attention to the green part covered by CCA. The length of this treated section was also measured using a digital calliper, following the method outlined in TZS 668:2021 and TANESCO (2022).

Figure 2

Extraction of Wood Samples from a Wooden Pole



(Source: Ssemaganda *et al.*, 2011)

2.3.3 Determination of CCA Retention

The same extracted samples from each pole were packed in polythene bags. The samples were ground into fine powder with a Wiley mill. The ground-treated wood was analysed for arsenic (As_2O_5), copper (CuO), and hexavalent chromium (CrO_3) content and retention (kgm^{-3}) using an Energy Dispersive X-ray Fluorescence Spectrometer model number X-MET8000 Optimum (ED-XRF) according to the procedures described by American Wood Protection Association (AWPA) Standard A9-0l (AWPA: 2006, AWPA, 2018; Aguayo *et al*., 2022).

2.3.4 Determination of CCA Distribution

The distribution of Chromated Copper Arsenate (CCA) within the treated poles was assessed by examining the spatial variation of preservative penetration and retention along both the longitudinal and radial directions of the poles. Key aspects considered included the uniformity of preservative concentration from the outer treated zone toward the core, as well as differences among the butt, middle, and top sections of each pole. Wood samples from these positions were analysed using an Energy Dispersive X-ray Fluorescence Spectrometer (ED-XRF; model X-MET8000 Optimum) to quantify the concentration of copper, chromium, and arsenic. The degree of variation in retention values across sections indicated the level of preservative distribution.

2.4 Data Analysis

Data analysis was performed using R version 4.3.1 and Statistical Package for the Social Sciences (SPSS) software tools. Descriptive statistics with mean, median, and standard deviation were done to evaluate the penetration level, retention level, and distribution of wood chemical preservatives. Additionally, modal severity and variations among samples subjected to different treatments were analysed, following the methodology established by Ssemaganda *et al*. (2011). To validate findings, the data were tested for normality and homogeneity of variance using the Shapiro-Wilk test and Levene's test, respectively, as recommended by Samuel *et al*. (2023). Understanding the relationship between preservative treatability and different pole sizes was achieved through regression analysis, aligning with the approach outlined by Ssemaganda *et al*. (2011). Furthermore, a one-way analysis of variance (Kruskal-Wallis H test) was employed to compare differences in wood preservative penetration and retention across various pole sizes. All statistical analyses were conducted at a 5% significance level. Specifically, the Kruskal-Wallis H test was applied to assess the impact of pole size on preservative penetration and retention, following the procedures described by Mugabi and Thembo (2018).

3.0 Results and Discussion

3.1 Results

3.1.1 Average Penetration and Moisture Content

From the results, the average penetration decreased as the pole size increased, from 30.01 mm for light poles to 24.97 mm for stout poles. The overall average penetration for all poles was 27.39 mm. The sapwood penetration was found to be lower for all pole classes, with the stout pole having the lowest penetration amount compared to the other classes (Table 2). The average moisture content was found to be 25.45%, with light poles having higher moisture content compared to other pole classes.

Table 2

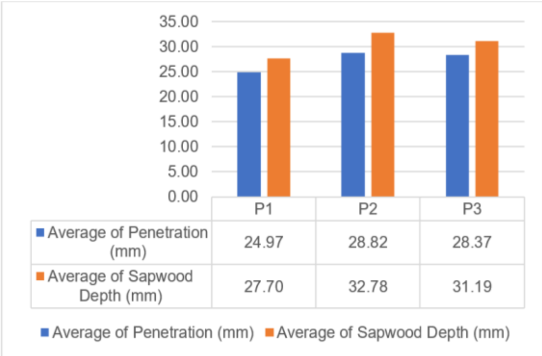
Average Penetration, Sapwood Depth and Moisture Content for Various Pole Classes

Pole Class	Average of Penetration (mm)	Average of Sapwood Depth (mm)	Average of MC (%)
Light	30.01	32.07	26.49
Medium	28.03	31.94	24.94
Intermediate	26.54	29.29	25.21
Stout	24.97	28.92	25.15
Overall mean	**27.39**	**30.56**	**25.45**

3.1.2 Distribution of Chemical Preservative Penetration Along Poles

Results revealed a notable disparity in the depth of Chromated Copper Arsenate (CCA) penetration across different positions along the poles. Specifically, Position 1 (1.5 m, i.e., theoretical ground level) exhibited a significantly higher degree of penetration compared to Position 2 (located at 50% of the pole length) and Position 3 (1.5 m from the top of the pole). This study indicates a comparatively diminished CCA penetration at Position 2 in contrast to Positions 1 and 3 along the pole (Fig. 3).

Figure 3
Average CCA Penetration and Sapwood Depth along the Poles



3.1.3 Average Retention and Moisture Content

The study found that the average retention for all pole classes was 21.41 kg/m^3. The light poles were observed to be the most treatable pole class, as they retained a high amount of CCA compared to the other pole classes. On the other hand, the medium poles were found to be less treatable in terms of CCA retention (Table 3). Retention of CCA among different pole classes ranged from 0 kg/m^3 to 56 kg/m^3. The study found that the moisture content was similar across all pole classes.

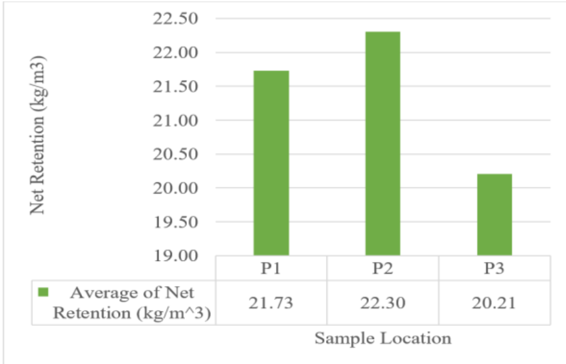
Table 3
Average Net Retention and Moisture Content for various pole classes

Pole Class	Average of Net Retention (kg/m^3)	Average of MC(%)
Light	25.50	26.49
Intermediate	20.28	25.21
Medium	18.54	24.94
Stout	21.33	25.15
Grand Total	**21.41**	**25.45**

3.1.4 Distribution of Chemical Preservative Retention along Poles

Results revealed significant variations in Chromated Copper Arsenate (CCA) retention across different locations on the poles. Specifically, Position 2 (located at 50% of the pole length) showed a significantly higher degree of retention compared to Position 1 (1.5 m or theoretical ground level) and Position 3 (1.5 m from the top of the pole). This study indicated that there is comparatively less CCA penetration at Position 3 as compared to Positions 1 and 2 along the pole (Fig. 4).

Figure 4
Average CCA Retention along the Poles



The one-way ANOVA showed significant differences ($p < 0.05$) in penetration among the pole classes. Significant differences ($p<0.05$) in CCA retention were also observed among the different pole sizes. Post hoc tests confirmed retention being significantly ($p < 0.05$) higher in light poles than in medium, intermediate and stout poles. However, differences in CCA penetration and retention in the light, medium and intermediate poles were not significant ($p > 0.05$). A weaker linear relationship was observed, where a positive correlation was observed between CCA penetration and retention ($r = 0.001$; $p < 0.05$), as shown in Fig. 5. A weaker linear relationship was also observed for all pole classes, as shown in Fig. 6.

Figure 5
Relationship between Retention and Penetration of CCA

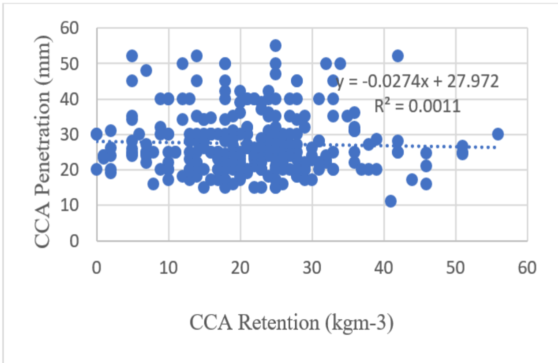
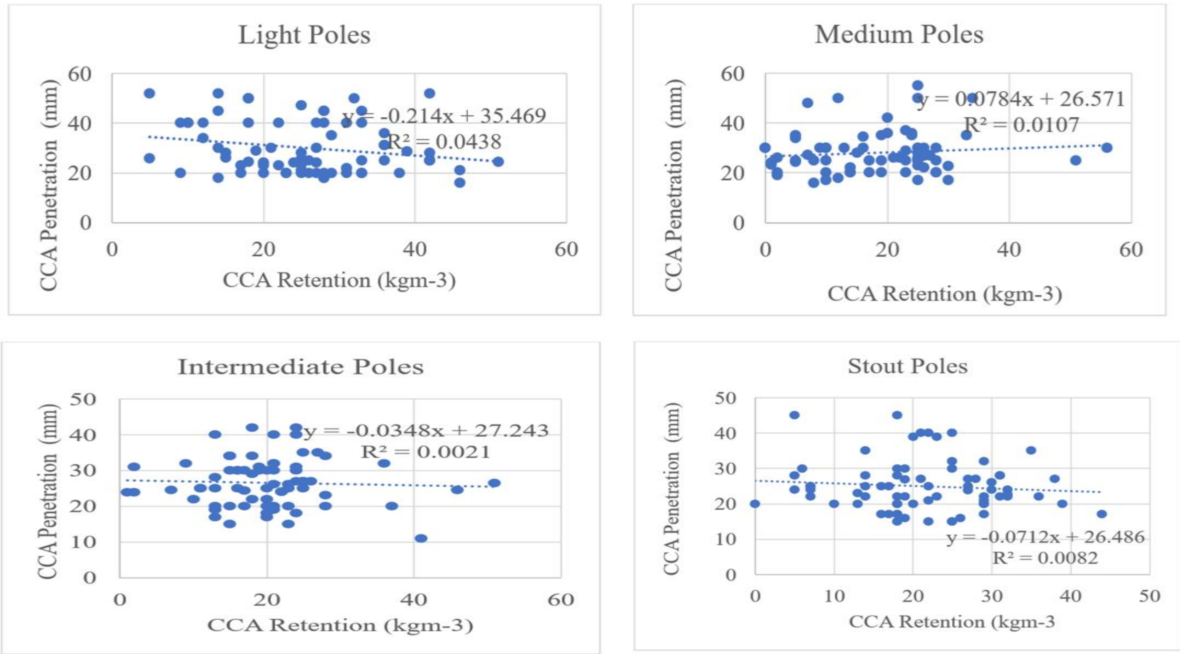


Figure 6

Interactive Scatter Plots Depicting the Penetration and Retention Levels of Chromated Copper Arsenate (CCA) Across Different Poles



3.2 Discussion

The study reveals a clear inverse relationship between pole size and average CCA penetration, with smaller poles (light poles) exhibiting greater penetration compared to larger poles (stout poles). This trend is consistent with other studies that have reported similar findings, where smaller cross-sectional areas allow for deeper penetration of preservatives due to the reduced resistance and shorter diffusion paths in the wood structure (Liese, 1985; Morris *et al.*, 1994; Reinprecht & Šupina, 2015). The overall average penetration of 27.39 mm across all pole classes suggests a satisfactory level of preservative distribution, albeit with room for improvement, particularly in larger poles where penetration was found to be less effective.

The lower penetration in sapwood across all pole classes, particularly in stout poles, raises concerns regarding the long-term durability and effectiveness of the treatment, as sapwood is generally more susceptible to decay than heartwood (Scheffer & Morrell, 1998; Oliveira & Silva, 2005). The moisture content results, with an average of 25.45%, suggest that the poles were treated within an optimal moisture range, as excessively high moisture content can hinder the absorption and retention of preservatives (Morris *et al.*, 1994).

The study's findings of significant variations in CCA penetration along different positions of the poles emphasise the value of considering pole geometry in treatment processes. The higher penetration at Position 1 (1.5 m from the theoretical ground level) compared to Positions 2 (midpoint) and 3 (1.5 m from the top) aligns with the expectation that the bottom of the pole, being in closer contact with the ground, would require more preservative to prevent decay (Lebow, 1996; Ruddick, 2000). The reduced penetration at Position 2, in particular, could be attributed to the natural tapering of poles, which may result in less preservative absorption in the middle sections.

The average retention of 21.41 kg/m³ across all pole classes is within acceptable industry standards, though the variation in retention among different pole classes suggests that treatment processes may need to be adjusted to ensure more uniform retention across all classes. Light poles demonstrated the highest retention, indicating that smaller poles allow for greater penetration and retain higher quantities of preservatives, enhancing their durability (Zabel & Morrell, 1992; James, 1988). On the other hand, the relatively low retention observed in medium poles may indicate a need to optimise the treatment process specifically for this class.

The uniformity in moisture content across different pole classes, averaging 25.45%, suggests that moisture content was not a significant factor influencing retention differences. However, similar moisture levels across classes highlight the importance of controlling other variables, such as treatment pressure and duration, to achieve optimal retention levels.

The significant variation in CCA retention along different positions of the poles, with Position 2 (midpoint) showing the highest retention, contrasts with the penetration pattern observed. This finding suggests that while penetration may be lower at the midpoint, the retention of preservatives is more effective in this region, possibly due to the concentration of sapwood or the distribution of preservatives during the treatment process (Kumar & Morrell, 2010). The lower retention at Position 3 (top of the pole) may indicate that this section is less exposed to environmental factors that would necessitate higher retention levels, although these differences could also be a concern for long-term durability.

The results of the one-way ANOVA highlight significant differences in penetration and retention among the different pole classes, with stout poles showing significantly higher retention. This finding is consistent with the hypothesis that larger poles, while having lower penetration, may compensate by retaining higher levels of preservatives, as suggested by Lebow and Winandy (1999). However, the weaker linear relationship observed between penetration and retention (r = 0.001) suggests that factors apart from penetration depth, such as wood density and treatment conditions, may play a more critical role in determining retention levels.

The positive correlation between penetration and retention, though weak, indicates the complexity of the interaction between these two variables (Ringman, 2017). While greater penetration typically facilitates higher retention, the variability observed in this study indicates that achieving optimal treatment outcomes requires a nuanced approach that considers multiple factors, including wood characteristics, treatment processes, and environmental conditions.

4.0 Conclusions and Recommendations

This study has found variations in the penetration, retention and distribution of chemical preservatives among different wooden pole classes in the Mufindi District. These dynamics are crucial for optimising preservation strategies and improving the durability and performance of wooden poles for various construction and infrastructure applications. Further research efforts should focus on refining treatment processes and developing novel preservative formulations tailored to specific wood types and environmental conditions. The study has provided important details about the penetration, retention, and distribution of Chromated Copper Arsenate (CCA) preservatives in different wooden pole classes, with light poles showing higher penetration and retention levels compared to larger poles, like stout poles. This suggests that pole size and wood structure play a critical role in determining the success of chemical preservative treatments.

The observed variation in CCA penetration and retention along different positions of the poles indicates the need for targeted preservative application, highlighting the necessity for adjusting treatment methods based on specific pole sections to enhance the overall durability and longevity of the poles. The study also found a slight but positive connection between CCA penetration and retention, suggesting that deeper penetration usually results in higher retention. However, other factors like wood composition and environmental exposure also significantly affect retention. Therefore, while penetration is important, it shouldn't be the only factor when assessing the effectiveness of preservative treatments.

The study highlights the need for a comprehensive approach that considers pole size, wood structure, and specific pole sections when applying chemical preservatives to optimise long-term performance and durability under varying environmental conditions. To strengthen these findings, a longitudinal study is recommended to monitor preservative penetration depth and retention rates over several years. Such research would offer helpful information regarding the durability and effectiveness of different treatment methods over time, while also promoting the development of innovative techniques and formulations to enhance preservative performance in wooden poles.

Based on the findings, it is recommended that preservative treatment protocols be customised according to pole size, with larger poles, like stout ones, receiving more intensive treatment to ensure adequate absorption. Monitoring and adjusting moisture content before treatment can also enhance preservative uptake, especially in poles with lower moisture content. To improve both penetration and retention, further research should focus on developing enhanced preservative formulations. Regular monitoring and retreatment of poles, where necessary, is advised to maintain durability over time.

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7.0 Declaration of Conflicting Interests

The authors declare no conflict of interest.

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