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COMPARATIVE FIELD PERFORMANCE OF ORGANIC AND COMMERCIAL PRESERVATIVES AGAINST BLUE STAIN FUNGI IN PINEWOOD

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ABSTRACT

The occurrence of blue stain fungi is one of the severe problems in the pinewood industry. This significantly reduces the market value of pinewood due to visible discoloration. This study evaluated the field performance of two plant extract based organic preservatives against boron-based inorganic preservatives for reducing the blue stain fungi development in pinewood. The organic preservatives are locally developed final solution with mud and final solution without mud and inorganic preservatives are commercially available Anti-blue and Anti-boron. The study used freshly cut pinewood specimens exposed for six months at three geographical regions in Sri Lanka i.e. (i) Bandarawela, (ii) Ratnapura, and (iii) Colombo. The effects of location, exposure condition, treatment type, and treatment timing were considered. Specimens were placed under sheltered and non-sheltered conditions, while preservative treatment was applied as early treatment and delayed treatment after cutting. Visible blue stain affected surface area was quantified using an image processing method applied to photographs taken of wood specimens. Untreated non-sheltered specimens in Bandarawela showed the highest visible blue stain development and were therefore used for detailed preservative performance comparison. Sheltered storage reduced visible discoloration compared with non-sheltered exposure. All preservative treatments reduced visible blue stain affected surface area compared with untreated specimens. Final solution with mud performed comparably with the tested commercial preservatives, while final solution without mud was effective but less protective. The findings indicate that early preservative treatment combined with sheltered storage is a practical approach for reducing visible blue stain development in freshly cut pinewood.

Keywords: *Blue Stain Fungi; Organic Preservatives; Pinewood; Sustainable Materials; Visible Discoloration.*

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1. INTRODUCTION

Timber has remained an important construction and industrial material for centuries because of its renewable nature, workability, and suitable for a wide range of structural and non-structural applications. Among commonly used softwoods, pinewood is used in furniture, interior finishing, packaging, temporary works, and other light construction applications because it is workable, relatively lightweight, and commercially accessible. In Sri Lanka, pinewood is also used in timber related applications where efficient post-harvest handling and storage are important.

Freshly cut pinewood is vulnerable to discoloration when environmental conditions favour fungal development. Blue stain fungi are a major cause of such discoloration in pinewood and other softwoods. They colonise sapwood and produce visible blue, grey, or dark staining on the wood (Jankowiak et al., 2021). Although blue stain does not always cause severe structural strength loss, it can reduce the visual quality and market acceptance of timber products (Humar et al., 2008). This is particularly important for appearance sensitive applications, where surface colour and visual uniformity affect product value. Therefore, controlling blue stain development is important for maintaining the commercial value of pinewood between felling, treatment, storage, and processing.

In practice, blue stain development can be reduced through preservative treatment and improved storage conditions. Fungal development on wood is strongly influenced by environmental conditions such as moisture availability, temperature, relative humidity, and drying periods (Hukka & Viitanen, 1999; Ringman et al., 2019). Inorganic commercial preservatives are commonly used to control staining and bio deterioration in timber. However, plant-based organic preservatives have drawn the attention because of concerns associated with some conventional wood protection chemicals. These plant-based preservatives have many natural compounds show antifungal or wood protective potential (Broda, 2020; Singh & Singh, 2012).

Two locally developed organic preservatives in Sri Lanka, Final Solution with Mud (FSWM) and Final Solution Without Mud (FSWOM), have shown potential for timber treatment applications and require further field-based evaluation and comparison against the currently used preservatives in the industry. Previous work has examined preservative uptake of plant extract based organic formulations using dipping diffusion methods, supporting the practical relevance of such treatment approaches (Hewage et al., 2024).

Although previous studies have examined wood preservatives and blue stain fungi separately, limited field-based evidence is available on the comparative performance of locally developed organic preservatives and commercial preservatives under Sri Lankan exposure conditions. The combined influence of geographical location, exposure condition, and treatment timing on blue stain development in freshly cut pinewood remains insufficiently studied.

Therefore, this study evaluates the field performance of FSWM and FSWOM in comparison with two commercially available preservatives, Anti-blue and Anti-boron. The study considers three different Sri Lankan geographical regions, sheltered and non-sheltered exposure conditions, and early and delayed treatment application. The findings are expected to support practical decision making on pinewood preservation and storage.

2. LITERATURE REVIEW

2.1 BLUE STAIN FUNGI IN PINEWOOD

Blue stain fungi are staining fungi that colonise wood, particularly the sapwood of softwoods, and produce blue, grey, or dark discoloration. In pinewood, staining is commonly associated with freshly felled timber, where exposed sapwood surfaces and high moisture levels provide favourable conditions for fungal colonisation (Jankowiak et al., 2021). Therefore the risk of visible staining is closely connected with post felling handling, storage, and treatment practices.

The major concern associated with blue stain is the deterioration of visual quality rather than direct structural failure. Humar et al. (2008) reported that blue stained wood may retain many of its basic material properties, but its appearance and commercial acceptability are reduced. This finding is important because blue stain becomes a practical quality problem even when the wood remains mechanically usable. For furniture, interior finishing, and other appearance sensitive applications, visible discoloration can reduce product value and market acceptance. Therefore, visible blue stain affected surface area is a relevant indicator for assessing timber quality and preservative performance in practical use conditions.

Freshly cut pinewood is especially vulnerable because cutting exposes sapwood surfaces before drying, processing, or preservative treatment (Brischke & Alfredsen, 2023). Jankowiak et al. (2021) showed that blue stain fungi can be isolated from freshly felled Scots pine logs, indicating the importance of post felling management in controlling staining. This supports the need to examine both preservative treatment and the timing of treatment application when evaluating methods for reducing visible blue stain development.

2.2 ENVIRONMENTAL FACTORS INFLUENCING BLUE STAIN DEVELOPMENT

The development of blue stain discoloration is strongly influenced by environmental conditions. Moisture availability is one of the most important factors because fungal activity generally requires sufficient water within the wood or on the wood surface. Ringman et al. (2019) emphasised that moisture critically affect for fungal development although the response may vary depending on wood species, treatment type, and exposure condition, Under field conditions, moisture availability is influenced not only by average relative humidity but also by rainfall, surface wetting, drying periods, and degree of exposure.

Temperature affects fungal development. Hukka and Viitanen (1999) demonstrated that mould growth on wooden materials is governed by the combined effects of temperature, relative humidity, and exposure duration. Therefore, differences in visible staining between locations should not be interpreted using relative humidity alone. Instead, temperature, wetting and drying cycles, duration of favourable conditions, and surface exposure should be considered together.

Storage condition is important because sheltering reduces direct rainfall exposure, thereby altering surface wetting and drying behaviour. Since the blue stain discoloration develops on exposed surfaces, reducing direct wetting may help limit staining severity. Therefore, the comparison between sheltered and non-sheltered exposure conditions is practically relevant for timber handling and storage.

2.3 WOOD PRESERVATIVES AND THE NEED FOR SAFER ALTERNATIVES

Wood preservatives are used to reduce biological deterioration, staining, and decay by limiting the ability of fungi and insects to colonise wood (Ayanleye et al., 2022). Inorganic commercial preservatives are widely used because of their effectiveness and market availability. However, concerns regarding environmental impact, leaching behaviour, and toxicity of some wood protection chemicals have encouraged the search for safer alternatives (Xing et al., 2020).

Boron based preservatives are commonly used in wood protection because Boron compounds show biological activity against fungi and insects. Lloyd et al. (2020) discussed the role of borate treatments in improving wood performance, particularly when used in systems designed to enhance protection. However, Boron based preservatives can be vulnerable to leaching under wet exposure conditions, which is an important consideration for outdoor, field-exposed timber applications. Hence, even though commercial preservatives remain important in timber protection, alternative formulations need to be evaluated under realistic exposure conditions.

The effectiveness of any preservative depends not only on antifungal activity yet on its ability to remain available on or within the wood under exposure conditions. This is particularly important where treated timber is exposed to rainfall, surface wetting, and drying cycles (Obanda et al., 2008). Therefore, the preservative performance should be evaluated under conditions that represent practical storage or field exposure rather than only under controlled laboratory settings.

2.4 PLANT BASED ORGANIC PRESERVATIVES AND TREATMENT METHODS

Plant based organic preservatives have gained increasing attention as potential alternatives to conventional wood protection chemicals. Natural compounds such as extractives, essential oils, tannins, alkaloids, and other plant derived substances show antifungal or insecticidal activity, depending on their chemical composition and target organism (Broda, 2020; Singh & Singh, 2012). These compounds are of interest because they may provide wood protection benefits while reducing reliance on more hazardous conventional chemicals.

Research on naturally durable heartwood has shown that wood extractives can contribute to biological resistance through both biocidal and non-biocidal mechanisms. Binbuga et al. (2008) noted that understanding the protective role of extractives can support the development of environmentally friendly wood preservatives. This is relevant to plant extract based preservative development because the performance of organic formulations may depend not only on direct antifungal toxicity but also on retention, surface coverage, and resistance to leaching.

However, bio-based preservatives require careful evaluation. López et al. (2021) showed that bio-based wood preservatives can be effective, yet their performance should be considered together with leaching behaviour and eco-toxicity. This is important for field exposed timber because rainfall and surface wetting may reduce preservative effectiveness if active compounds are not sufficiently retained. Therefore, field based comparisons with commercial preservatives are necessary before plant based formulations can be recommended for practical use.

Previous work on plant extract based organic preservatives has examined preservative uptake using dipping diffusion treatment. That suggests the practical relevance of this method for applying organic formulations to timber (Hewage et al., 2024). However, uptake behaviour alone does not fully establish field performance against visible blue stain discoloration, under varying environmental exposure conditions.

2.5 RESEARCH GAP

The reviewed literature shows that blue stain fungi reduce the visual quality and commercial value of pinewood. The environmental exposure influences visible staining, and preservative treatment is an important method of control. It shows growing interest in plant based wood preservatives, although their field performance depends on treatment method, retention, exposure, and environmental conditions. However, limited field based evidence is available on the comparative performance of plant extract based organic preservatives and commercially available inorganic preservatives for reducing visible blue stain affected surface area in pinewood under Sri Lankan exposure conditions. This gap is addressed in the present study through a field based comparative evaluation of organic and commercial preservatives under different environmental exposure and treatment timing conditions.

3. METHODOLOGY

3.1 SITE SELECTION

A field based experimental approach was used to evaluate the performance of organic and commercial preservatives in reducing visible blue stain development on pinewood. The study was conducted over a six-month exposure period using freshly cut pinewood specimens placed at three different geographical locations in Sri Lanka i.e. (i) Bandarawela, (ii) Ratnapura, and (iii) Colombo.

The three locations were selected to represent different field exposure conditions in terms of average temperature and relative humidity. Climate data obtained from Climate-Data.org (refer Table 1) were used to identify the general climatic characteristics of the selected locations.

Table 1: Average temperature and relative humidity of selected locations

Selected Site	Annual Average Temperature (°C)	Average RH (%)
Bandarawela	21.2	82.8
Ratnapura	24.3	87.0
Colombo	26.5	79.5

The selected sites were not intended to represent laboratory controlled conditions; rather, they were used to compare preservative performance under practical field exposure conditions where temperature, humidity, rainfall exposure, and drying behaviour vary.

3.2 SAMPLE PREPARATION

Freshly cut pinewood was obtained from selected pinewood plantation sites. The specimens were prepared from randomly selected freshly cut trees to reduce sampling bias. A total of 162 pinewood specimens were prepared for the study, with 54 specimens allocated to each location. Each specimen had a cross section of 50 mm × 50 mm and a length of 450 mm.

The experimental arrangement included untreated control specimens and preservative treated specimens. For each test condition, three replicate specimens were used, and the reported values were calculated as the average of the three replicates.

3.3 PRESERVATIVE TREATMENTS

Four preservative treatments were evaluated. Two plant extract based organic preservatives were used i.e. (i) FSWM and (ii) FSWOM. These preservatives were developed at the ProGreen Laboratory, Department of Civil Engineering, University of Moratuwa, and are associated with local patent numbers 21896 and 21911 (Halwatura & Mendis, 2023). The formulations are based on leaf extracts of *Gliricidia sepium*, *Tithonia diversifolia*, and *Mikania micrantha*. FSWM includes a prepared paddy field mud component, whereas FSWOM is prepared without the mud component. Previous work has examined preservative uptake of similar plant extract based organic formulations using dipping diffusion treatment (Hewage et al., 2024). The other two treatments were commercially available inorganic boron-based preservatives, Anti-blue and Anti-boron. These preservatives are commonly used in the Sri Lankan pinewood industry and were included as reference commercial treatments for comparison with the organic formulations. The dipping method was used for preservative application. Each treated specimen was immersed in the relevant preservative solution for 48 hours. Untreated specimens were maintained as control samples.

3.4 EXPOSURE CONDITIONS AND TREATMENT TIMING

Two exposure conditions were considered: non-sheltered and sheltered. Non-sheltered specimens were placed at the site and exposed to direct field conditions, including rainfall and ambient environmental conditions. Sheltered specimens were placed in a protected area near the site, where direct rainfall was avoided while still allowing exposure to the surrounding ambient environment.Treatment timing was considered. Early treatment refers to preservative application started two days after cutting. Delayed treatment refers to preservative application started twelve days after cutting. These two treatment timings were used to evaluate whether a short delay after cutting influenced the blue stain development after treatment. Untreated specimens were used as control specimens. The experimental variables, therefore, included location, exposure condition, treatment type, and treatment timing. Each site included untreated specimens and treated specimens under sheltered and non-sheltered conditions, with three replicates for each test condition. Table 2 presents the variables and levels of those variables used in the experiment.

Table 2: Experimental variables and levels

Variable	Levels
Location	Bandarawela, Ratnapura, Colombo
Exposure condition	Sheltered, Non-sheltered
Treatment type	Untreated, FSWM, FSWOM, Anti-blue, Anti-boron
Treatment timing	Early treatment: 2 days after cutting, Delayed treatment: 12 days after cutting
Replicates	Three specimens per test condition

3.5 MEASUREMENT OF VISIBLE BLUE STAIN AFFECTED SURFACE AREA

The assessment focused on visible blue stain discoloration on the surface of the pinewood specimens. Inspections were carried out once per month for six months. During each inspection, photographs were taken from all four longitudinal faces of each specimen. The visible blue stain affected surface area was quantified using a Python based image processing procedure adapted from the affected pixel area estimation approach used by Islam and Rafiqul (2015). Each image was converted into grayscale and then processed as a binary image using a calibrated threshold value to separate visibly stained regions from unstained wood surface areas. The threshold was calibrated by comparing image processing outputs with manual visual classification of representative images. The image processing procedure is presented in Figure 1.

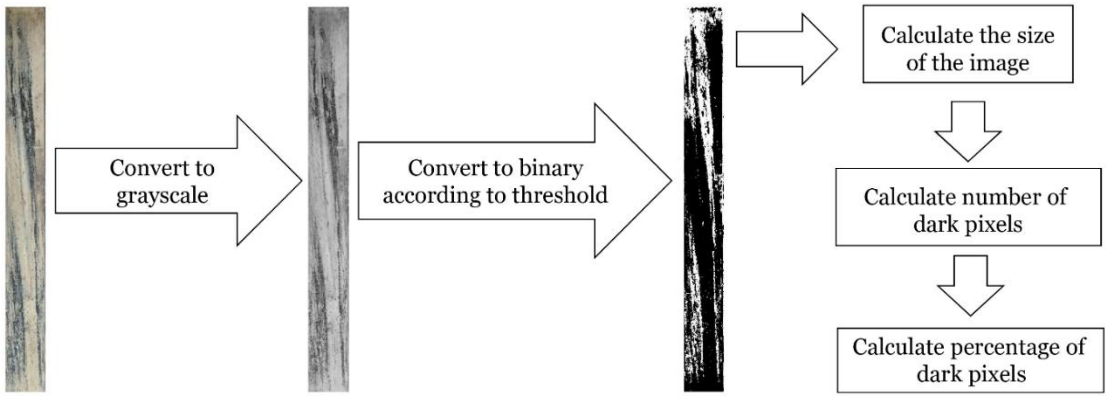

Figure 1: Image processing procedure used to quantify visible blue stain affected surface area

The blue stain affected surface area of each photographed face was calculated as the ratio between the number of stained pixels and the total number of visible wood surface pixels. The affected surface area percentage was calculated using Eq. (1):

$$A_b = \frac{A_S}{A_t} \times 100 \qquad (01)$$

where, A_b = visible blue stain affected surface area (%), A_s = stained pixel area and A_t = total visible wood surface pixel area. The final value for each specimen was obtained by considering all four photographed faces. The values reported for each test condition were calculated as the mean of three replicate specimens. Therefore, the reported percentage represents visible blue stain surface coverage rather than fungal biomass or internal fungal colonisation.

4. RESULTS

4.1 VISIBLE BLUE STAIN DEVELOPMENT IN UNTREATED NON-SHELTERED SPECIMENS ACROSS LOCATIONS

Visible blue stain affected surface area increased with exposure time in untreated non-sheltered pinewood specimens at all three locations. Therefore, this section presents the untreated control condition only. However, the extent of discoloration differed among locations (refer Figure 2). After six months, Bandarawela recorded the highest visible blue stain affected surface area, with 19.60% of the photographed surface area affected. Ratnapura recorded 12.48%, while Colombo recorded the lowest value, at 10.58%.

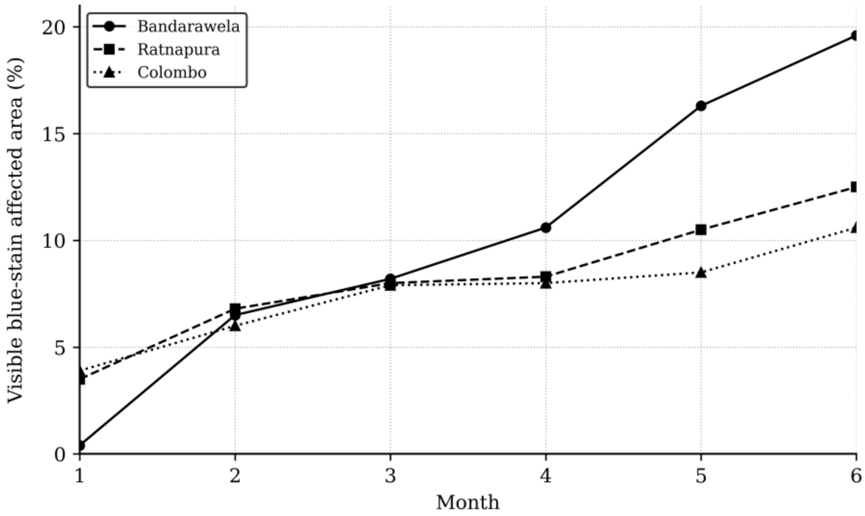

Figure 2: Variation of visible blue stain affected surface area in untreated non-sheltered pinewood specimens across selected locations

The results show that location influenced the progression of visible blue stain discoloration under non-sheltered field exposure. Therefore, Bandarawela was selected as the baseline condition for the detailed preservative effectiveness comparison because it represented the most severe visible blue stain development observed among the untreated non-sheltered specimens.

4.2 EFFECT OF SHELTERED AND NON-SHELTERED EXPOSURE CONDITIONS ON UNTREATED SPECIMENS

This comparison was also carried out using untreated control specimens only, in order to examine the influence of exposure condition before comparing preservative treatments. Sheltering reduced visible blue stain development in untreated pinewood specimens. In Bandarawela, untreated non-sheltered specimens showed a continuous increase in visible blue stain affected surface area over the six months of exposure period, reaching 19.60% at the end of the observation period. In comparison, untreated sheltered specimens recorded 9.27% affected surface area after six months (refer Figure 3).

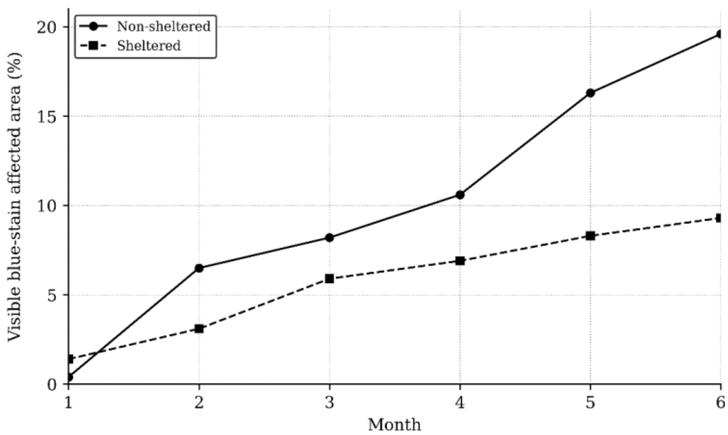

Figure 3: Variation of visible blue stain affected surface area under sheltered and non-sheltered exposure in Bandarawela

The blue stain affected area under sheltered exposure was less than half of that recorded under non-sheltered exposure. This indicates that avoiding direct rainfall reduced visible surface discoloration, even though the specimens remained exposed to the surrounding ambient environment.

4.3 EFFECT OF PRESERVATIVE TREATMENT UNDER DELAYED APPLICATION

The delayed treatment condition refers to preservative application started twelve days after cutting. Under the non-sheltered Bandarawela condition, all preservative treated specimens showed substantially lower visible blue stain affected surface area than untreated specimens throughout the observation period. The results are shown in Figure 4.

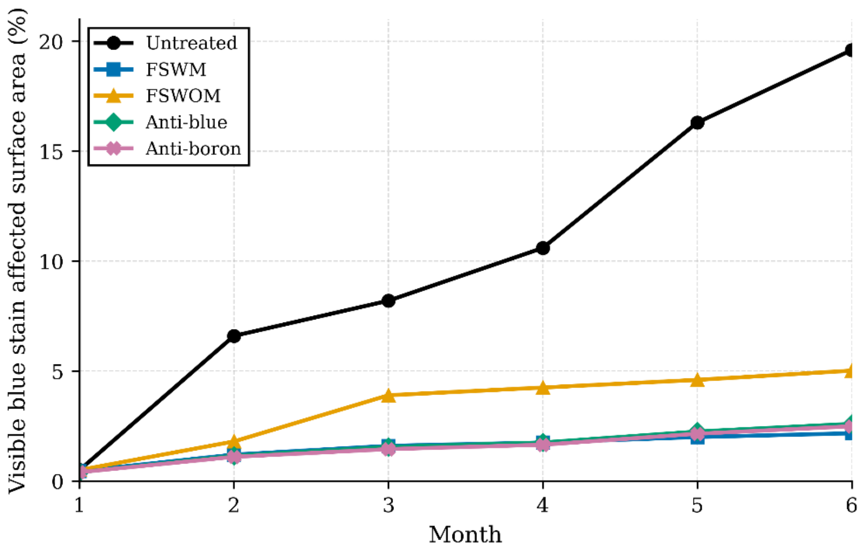

Figure 4: Visible blue stain affected surface area of untreated and delayed treatment pinewood specimens in Bandarawela under non-sheltered exposure condition

The values presented in Figure 4 are based only on non-sheltered specimens exposed in Bandarawela and are not averages across the three study locations.

After six months, untreated non-sheltered specimens recorded 19.60% visible blue stain affected surface area. In contrast, FSWM recorded 2.17%, FSWOM recorded 5.02%, Anti-blue recorded 2.60%, and Anti-boron recorded 2.49%. These results show that all preservative treatments reduced visible blue stain development compared with untreated specimens. Among the organic preservatives, FSWM showed the lower affected surface area and performed competitively with the commercial preservatives.

4.4 EFFECT OF PRESERVATIVE TREATMENT UNDER EARLY APPLICATION

The early treatment condition refers to preservative application started two days after cutting. Similar to the delayed treatment condition, early preservative application reduced visible blue stain affected surface area compared with untreated non-sheltered specimens in Bandarawela (refer Figure 5). The values presented in Figure 5 are based only on non-sheltered specimens exposed in Bandarawela.

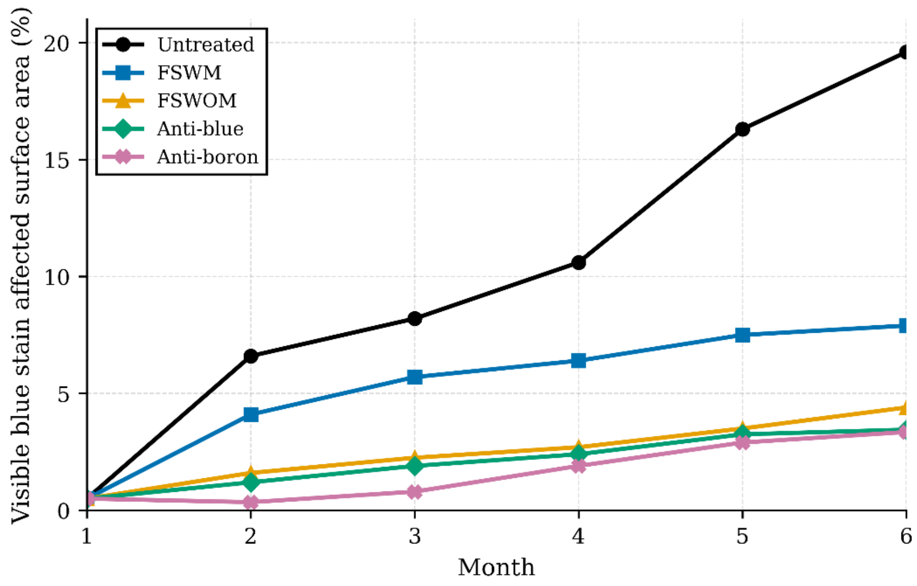

Figure 5: Visible blue stain affected surface area of untreated and early treatment pinewood specimens in Bandarawela under non-sheltered exposure condition

The comparison between early and delayed treatment showed that both treatment timings reduced visible blue stain affected surface area compared with untreated specimens. However, the differences between early and delayed treatment were not consistent across all preservatives. Therefore, the results cannot not be interpreted as proving that treatment timing has no effect under all conditions. They indicate that preservative application within the tested period remained effective in reducing visible discoloration.

4.5 COMPARATIVE PRESERVATIVE EFFECTIVENESS AFTER SIX MONTHS

The final six month values under the severe non-sheltered Bandarawela condition were used to compare preservative effectiveness. The reduction in visible blue stain affected surface area was calculated relative to untreated specimens. The results are shown in Table 3.

Table 3. Final visible blue stain affected surface area and reduction compared with untreated non-sheltered specimens in Bandarawela

Treatment	Visible Blue Stain Affected Surface Area (%)	Reduction Compared with Untreated Specimens (%)
Untreated	19.60	—
FSWM	2.17	88.93
FSWOM	5.02	74.39
Anti-blue	2.60	86.73
Anti-boron	2.49	87.30

The final comparison shows that FSWM produced the lowest visible blue stain affected surface area among all tested preservatives under this condition. Anti-boron and Anti-blue showed strong performance, with final affected areas close to FSWM. FSWOM reduced visible blue stain development compared with untreated specimens, yet its final affected surface area was higher than FSWM and the two commercial preservatives.

Therefore, the results indicate that FSWM showed competitive performance against the commercial preservatives, while FSWOM was effective yet less protective under the severe non-sheltered Bandarawela condition.

5. DISCUSSION

5.1 INFLUENCE OF LOCATION AND FIELD EXPOSURE ON VISIBLE BLUE STAIN DEVELOPMENT

The variation in visible blue stain affected surface area across locations confirms that field exposure conditions influenced discoloration development. Although Ratnapura recorded the highest average relative humidity among the selected locations, Bandarawela showed the highest visible blue stain coverage, indicating that relative humidity alone cannot explain the observed pattern. This interpretation is consistent with Hukka and Viitanen (1999), who showed that mould development on wooden materials depends on the combined influence of temperature, relative humidity, and exposure duration. Ringman et al. (2019) similarly emphasised that moisture availability should be understood together with wood condition, exposure, and treatment. Rice et al. (2008) showed that blue stain fungi may differ in their temperature adaptation, further supporting the view that environmental response is not controlled by a single climatic parameter. Therefore, the higher discoloration in Bandarawela may be related to the combined influence of surface wetting, drying behaviour, temperature, and exposure duration rather than a single climatic parameter.

The lower discoloration observed under sheltered exposure further confirms the practical value of reducing direct rainfall exposure during pinewood storage. Since sheltered specimens remained exposed to the surrounding ambient environment, the reduction in visible blue stain development suggests that direct surface wetting played an important role in the observed discoloration pattern.

5.2 PERFORMANCE OF ORGANIC AND COMMERCIAL PRESERVATIVES

All preservative treatments reduced visible blue stain affected surface area compared with untreated specimens under the severe non-sheltered Bandarawela condition, confirming the practical value of preservative treatment for freshly cut pinewood. However, the treatments did not perform equally. FSWM showed the strongest performance among the organic preservatives and achieved a similar level with Anti-blue and Anti-boron. FSWOM was effective compared with untreated specimens but less protective than FSWM and the commercial treatments.

The observed difference between FSWM and FSWOM is consistent with broader literature showing that plant based preservatives can have wood protective potential but require formulation specific evaluation. Natural compounds and plant extractives may show antifungal or protective effects, yet their effectiveness depends on chemical composition, target organism, wood species, exposure conditions, and formulation stability (Broda, 2020; Singh & Singh, 2012). Extractives may contribute to wood protection through both biocidal and non-biocidal mechanisms (Binbuga et al., 2008).

The stronger performance of FSWM may be related to formulation composition, particularly the presence of the paddy field mud component, which may have contributed to surface coverage, retention, or resistance to removal during wetting and drying cycles.

However, these mechanisms were not directly tested in this study. Since bio based preservative performance depends not only on biological activity but also on retention and leaching behaviour (López et al., 2021), the stronger performance of FSWM can be interpreted as an observed formulation level outcome.

The strong performance of Anti-blue and Anti-boron is consistent with the established role of commercial preservatives in controlling bio deterioration and staining. Boron-based treatments are widely discussed in wood protection because boron compounds can be effective against fungi and insects (Lloyd et al., 2020). However, their performance under wet exposure may be influenced by leaching.

5.3 EFFECT OF TREATMENT TIMING

The comparison between early and delayed treatment showed that both treatment timings reduced visible blue stain affected surface area compared with untreated specimens. This suggests that preservative application within the tested period remained effective in reducing visible discoloration. However, the differences between early and delayed treatment were not uniform across all preservatives. Therefore, the results should not be interpreted as proving that treatment timing has no effect under all circumstances.

From a practical perspective, early treatment remains preferable because freshly cut pinewood is vulnerable to blue stain development during storage and handling. Jankowiak et al. (2021) showed that blue stain fungi can be isolated from freshly felled pine logs, supporting the importance of post felling management. The present results suggest that preservative treatment can reduce visible discoloration even when application is delayed within the tested period, but rapid treatment and sheltered storage would still be safer recommendations for industry practice.

5.4 PRACTICAL IMPLICATIONS AND LIMITATIONS

The findings have practical implications for the pinewood industry in Sri Lanka. Freshly cut pinewood should be protected from direct field exposure where possible, because sheltered storage substantially reduced visible blue stain development. Preservative treatment is also important under severe exposure conditions. Among the tested organic preservatives, FSWM showed the greatest practical potential because it showed similar effectiveness to the commercial inorganic preservatives. Since the organic formulations are based on locally available plant materials, they may support more locally adaptable timber protection practices and reduce dependence on imported or commercially sourced inorganic preservatives. However, wider industrial promotion requires further studies on cost, production scalability, preservative retention, leaching, and long term durability.

Several limitations should be acknowledged. The comparative ranking of preservatives should be interpreted as context specific to the severe non-sheltered Bandarawela condition, and further analysis is required before generalising treatment performance across all Sri Lankan field exposure conditions. The image processing method quantified visible blue stain affected surface area, not fungal biomass or internal fungal colonisation. Grayscale thresholding may also classify some dark surface features as stained regions, although this was reduced by calibration against manual visual classification. Future work should include leaching tests, preservative retention measurements, fungal identification, evaluation of the mud component, and longer exposure periods.

6. CONCLUSIONS

This study evaluated the field performance of two plant extract based organic preservatives, FSWM and FSWOM, against two commercially available inorganic Boron-based preservatives, Anti-blue and Anti-boron. The study examined the reduction of visible blue stain affected surface area in pinewood under Sri Lankan field exposure conditions. Visible blue stain development varied across locations, with untreated non-sheltered specimens in Bandarawela recording the highest affected surface area after six months. Sheltered storage reduced visible discoloration by approximately 52.7% compared with non-sheltered exposure in Bandarawela, indicating that protecting freshly cut pinewood from direct rainfall can help limit blue stain development during storage and handling. All preservative treatments substantially reduced visible blue stain affected surface area compared with untreated specimens. Under the severe non-sheltered Bandarawela condition, FSWM produced the highest reduction, approximately 88.9%, followed by Anti-boron at 87.3%, Anti-blue at 86.7%, and FSWOM at 74.4%. These results show that FSWM performed comparably with the commercial preservatives, while FSWOM was effective compared with untreated specimens yet less protective than FSWM and the commercial treatments. Both early and delayed treatment applications reduced visible blue stain development, although the timing effect was not uniform across all preservatives. Therefore, early preservative treatment combined with sheltered storage is recommended as the safer practical approach for freshly cut pinewood. Future studies should examine preservative retention, leaching resistance, long term field durability, fungal species identification, and the specific contribution of the mud component to FSWM performance.

7. ACKNOWLEDGEMENTS

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