

## Impact of microwave irradiation pretreatment on preservative retention and durability of outdoor-exposed Norway spruce

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### ABSTRACT

Norway spruce (*Picea abies* L. Karst.) is a commercially valuable species, but has low permeability and susceptibility to decay, which requires an effective preservative treatment. In this study, the effect of microwave (MW) pretreatment on preservative retention and durability of wood during 30 months of outdoor exposure was investigated. MW-treated specimens showed a significant increase in preservative retention of borax-boric acid (BBA), with MW 36 treated specimens showing a retention of 40.79 kg/m<sup>3</sup> compared to 7.90 kg/m<sup>3</sup> for untreated controls. Durability assessment revealed that the MW treated specimens remained decay-free at higher energy levels (MW 28, MW 32, MW 36), whereas the untreated controls reached decay ratings of 3 in open conditions and 2 in shaded environments. Structural and chemical changes, including increased permeability, lignin content and crystallinity might have contributed to the increased resistance of MW-treated wood to fungal decay. The study also highlights the influence of climatic factors on the progression of decay, with MW pretreatment resulting in significant improvement in resistance to moisture-induced degradation. While lower MW energy levels (MW 20, MW 24) showed slight fungal growth, higher energy levels provided sustained protection, establishing the effectiveness of MW pretreatment as a promising technique to augment preservative retention and improve the in-service durability of wood. Future research should therefore investigate the mechanical effects, economic feasibility, and long-term performance of different commercial species in the field under different climatic conditions. The present study demonstrates that microwave pretreatment synergistically enhances the efficacy of BBA, which is a waterborne leachable but relatively safe wood preservative, potentially diminishing exclusive reliance on traditional toxic chemical preservatives to improve wood durability.

### 1. Introduction

Wood is currently one of the most important and in-demand material for construction purposes. It is one of the most adaptable raw materials that has been used for generations in the construction industry, furniture manufacturing, and a variety of other uses. Recent increases in wood utilization can be attributed to its natural origin, sustainable sourcing, wide availability, and desirable properties [1,2]. However, the resistance of commercially important wood species to wood decaying basidiomycetes, termites, insects, and marine borers has been a topic of great interest to wood researchers worldwide for many decades.

Assessing the suitability of a timber species for a particular building project relies heavily on its durability, which is a fundamental performance factor. It is worth noting that the sapwood of all wood species usually has a remarkably weak resistance, such that published natural durability values refer exclusively to the heartwood of a species [3]. Heartwood typically contains natural extractives that reduce permeability and confer intrinsic decay resistance, while sapwood usually shows higher permeability and greater preservative uptake.

The degradation of wood while in service is mainly caused by biotic and abiotic factors in both terrestrial and marine environments. Abiotic factors such as rapid weathering, UV radiation, high humidity and

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temperature fluctuations often instigate wood decay and pave the way for biotic decay by insects, fungi, bacteria, nematodes, molluscs, and crustaceans [4]. The longevity of wooden objects is often attributed to their natural resistance to decay and their susceptibility to the surrounding environmental conditions. The onset and intensity of decay of wood products can vary considerably due to fluctuations in moisture, soil nutrient content and pH of the soil, temperature variations, the presence of nutrients in the wood, and the structure and condition of the cell wall components [5,6]. Moreover, predicting the durability of some wood species is complex, mainly due to its wide range of uses and the associated different test methods [7].

A particular wood is considered inherently durable when it can resist attack by wood-destroying agents without significant alteration of its physical or chemical properties [8]. Selecting an appropriate species for the intended application is therefore essential to slow natural degradation. To evaluate durability, researchers use two complementary approaches: controlled laboratory tests, which typically expose small specimens made from the heartwood to specific biodeteriogens under standardized conditions [9]; and field exposure trials, which assess performance of wood in outdoor service either in direct ground contact or above ground.

The results of field tests are generally favoured for determining the durability class, as the wood is exposed to a variety of biodeteriogens in the field under natural use conditions. These organisms colonise the wood sequentially and can interact synergistically with abiotic factors [8–10]. Field trials, despite prolonged exposure periods and intensive monitoring, provide the most definitive assessments of wood durability and service life. Service life is primarily determined by two key factors: a) the natural resistance of a particular wood species and b) the type and severity of hazards to which it is exposed [11]. The second factor can be regulated by limiting the wood's susceptibility to biotic and abiotic deterioration through chemical wood protection formulations or modifying its chief polymeric components [12].

This study focusses on the durability of Norway spruce wood (*Picea abies* L. Karst.). Norway spruce wood is highly valued for its numerous indoor and outdoor uses [13], for the construction of musical instruments; especially for the manufacturing of violin tops and soundboards [14]. However, studies have shown that Norway spruce wood is not very durable as it is very susceptible to stain fungi [15] and is easily attacked by *Gloeophyllum abietinum* [16] and other wood decaying fungi. Therefore, the treatment of Norway spruce wood with wood preservatives is an indispensable prerequisite. However, Norway spruce wood is characterised by a low permeability of the heartwood due to the closed pits, which generally leads to a low preservative retention in the wood. The treatment of wood with microwaves (MW), which is considered a green modification technique, has been reported in recent times to be effective in improving the treatability and impregnability of several wood species with low permeability to enhance impregnation [17–20] and therefore, was adopted in our study. When wood is exposed to electromagnetic radiation of MW, this leads to rapid heating of the water molecules present in it, causing vapor pressure to build up. This pressure leads to the rupture of weak anatomical elements of wood like ray cells and pit membranes, ultimately creating channels that facilitate the flow of liquids or gases and increase the permeability [19,20]. This results in better mobility of treating chemicals and improved preservative retention and distribution [21]. Rapid heating of wood from the core, during MW can potentially cause the restructuring of the main polymer elements and inflict changes in their proportion to an extent that can make wood unpalatable for decay pathogens, but, the shorter treatment times associated with MW pretreatment in general may lead to an insignificant change unlike thermal modification. Previous studies highlighted that MW modified wood at different energy intensities coupled with different water borne preservative formulations exhibited better resistance in comparison to untreated controls under laboratory conditions [12]. At the same time, it has also been reported that the application of microwave treatment leads to a slight increase in acidity

in the wood [22], a change that could favour decay by certain fungal species despite improved preservative uptake. Laboratory assays expose wood to specific biodeteriogens under controlled conditions and may not capture the complexity of outdoor environments. Therefore, it is crucial to investigate the response of MW-modified wood in the field to evaluate its biological resistance and assess the suitability of modified wood for potential commercial utilization. Nevertheless, the research conducted to date on microwave pretreatment of wood has not thoroughly investigated these concerns.

While the effect of microwave pretreatment in improving the permeability of wood is well documented, this research focuses on evaluating how microwave-induced micro-voids within the wood matrix contribute to increased preservative retention and distribution, making it more resilient to incipient decay in service. It is further hypothesized that these micro voids may facilitate deeper penetration of preservative into the cell walls, and upon drying and subsequent mobilization, a better fixation within the microstructure could be expected leading to reduced leaching behaviour [12] and subsequently better performance in use.

The test specimens used for this assessment comprised mixed sapwood and heartwood, and therefore tissue-specific differences in performance was not considered. The primary aim of the present work was to elucidate the performance of a borax - boric acid (BBA) -based wood preservative, applied to microwave-pretreated wood to evaluate its outdoor durability in real use conditions. This preservative is well recognized as a fairly safe wood protection system indoors but largely unsuitable for outdoor applications due to its propensity for leaching.

## 2. Materials and methods

### 2.1. Wood material

Seasoned boards of imported Norway spruce (*Picea abies* L. Karst.) with no visible defects or fungal contamination were used for the study. Boards were further processed into specimens of the desired dimensions (30.5 (length) × 3.5 (width) × 3.5 (height) cm) for the durability test following the protocols suggested by Poonia and Tripathi [22] and our initial standardization trials.

### 2.2. Specimen preparation

Specimens having mixed sapwood and heartwood were used for durability test in outdoors above ground, in open (corresponding to use class 3.2 as per EN 335) [23] and under shade (corresponding to use class 2 as per EN 335) [23] conditions. Boards were converted into 30.5 (length) × 3.5 (width) × 3.5 (height) cm specimens. Relatively straight-grained specimens were selected for the study that showed no visual anomalies. The specimen size was modified from that suggested by Rapp and Augusta (2004) [24], to optimize variation [25]. Specimens were first immersed in deionized water for 48 h to mimic their green state [26]. The specimens were then conditioned for a period of 24 h at 60 % relative humidity (RH) and a temperature of 20 °C. For each test series, 42 specimens were used (6 replicates for each treatment set) totalling 84 specimens (Table 1). For the experiment, the initial moisture content (IMC) of the specimens (with standard deviation in parentheses) was determined on an oven-dry (OD) basis according to BIS (1991) [27] for 30 randomly selected specimens from the batch. The average IMC was determined to be 46.9 % (±1.8) % before the start of the experiments.

### 2.3. MW pretreatment procedure

The MW pretreatment was carried out in a microwave heating device (Model 30SC3, IFB Industries, India) operating at a frequency of 2.45 GHz and a maximum output power of 900 W. The details of the MW pretreatments are described in Table 1.

**Table 1**  
Specification for MW pretreatment and sample distribution for above ground durability test.

Treatment Name	Applied MW Energy (MJ/m <sup>3</sup> )	MW Treatment Time (Seconds)	No. of Replicates (Set 1: Above ground open condition)	No. of Replicates (Set 2: Above ground condition under shade)	Total
MW 20	700	233	6	6	12
MW 24	840	280	6	6	12
MW 28	980	327	6	6	12
MW 32	1120	374	6	6	12
MW 36	1260	421	6	6	12
CP (No MW + BBA)	No MW + Preservative	–	6	6	12
C (No MW + No BBA)	No MW	–	6	6	12
<b>Total number of specimens</b>					<b>84</b>

All specimens except the controls were individually exposed to MW irradiation and the parameters of the MW pretreatments were defined based on the MW power and volume of the specimens as suggested by Kol and Çayir (2021) [28] and our preliminary experiments. MW pretreatment was performed on wood specimens with an IMC of about 47% at five different energy levels and two sets were kept as untreated controls (Table 1). The MW energy intensity was calculated using the following equation,

$$E = \frac{P \times T}{V}$$

where  $E$  is the applied energy (MJ/m<sup>3</sup>),  $P$  is the MW power (W),  $T$  is the total exposure time for each treatment (sec), and  $V$  is the sample volume for each treatment (m<sup>3</sup>). The variables  $P$  and  $V$  remained constant during each treatment, so that  $T$  was the only variable that changed to affect  $E$ . For ease of calculation, the overall volume of wood specimens was rounded up and considered as 0.00030 m<sup>3</sup>.

After completion of the MW pretreatment, the specimens were removed from the MW device and the weight percentage loss (WPL) was calculated as proposed in Refs. [21,28] before subjecting those to further experiments.

#### 2.4. Preservative formulation

The preservative solution BBA was chosen for its potential to resist the biodegradation of wood. A 6% solution of BBA was prepared by dissolving 30 g of borax and 30 g of boric acid in 1 L of lukewarm deionized water.

#### 2.5. Pressure impregnation

After MW pretreatment, the specimens were weighed with an accuracy of 0.01 g and immersed in the preservative solution. Immersion was carried out for 20 h in a plastic vessel under laboratory conditions. Specimens were completely immersed in the preservative solution and weighed on top to prevent floating. At the end of the 20-h immersion, the specimens were pressure impregnated in a laboratory-scale impregnation chamber using the full-cell method, where initial vacuum (−0.085 MPa) was exercised for 20 min, then high pressure (1 MPa) for 3 h, and finally vacuum (−0.085 MPa) for 20 min. Afterwards, specimens were immersed for a further 20 h at atmospheric pressure to determine retention as accurately as possible. At the end, specimens were carefully wiped to remove any dripping preservative and weighed to the nearest 0.01 g. After impregnation and subsequent weighing,

specimens were conditioned at 20 °C and 65 ± 5% air relative humidity (RH) for eight weeks for better fixation and mobilization of the preservative before exposing those for the durability test.

#### 2.6. Outdoor accelerated durability test above ground

The unmodified and MW pretreated specimens were stacked in a double layer. To mimic the natural state of use and some cladding and flooring constructions, the specimens were assembled without connectors or joints. The wood specimens consisted of two layers; one layer was placed on top of the other, with the top layers spaced 25 mm laterally from the bottom layers and the specimens placed 25 cm above the ground on an open platform [29,30]. No spacers or cross braces were used in between to ensure efficient moisture entrapment by rainfall; accelerating the rate of degradation. The test was conducted for a period of 30 months from February 2021 to July 2023 at the test site of the Wood Preservation Discipline, Forest Products Division, Forest Research Institute, Dehradun.

The first set of specimens (Set 1: Table 1) was kept outdoors in direct sunlight, natural air and rainfall representing class 3.2 as proposed in EN 335 [23]. This was done to reproduce the exact conditions of use of wood-based cladding and construction materials outdoors. Another set (Set 2: Table 1) was kept in the shade of a thatched bamboo hut at the test site representing use class 2 as per EN 335 [23]. This was chosen to mimic the use conditions of wood products with very little to no exposure to direct sunlight and rain. The specimens were inspected every 6 months for the first three cycles and annually thereafter [30]. Decay was assessed on the basis of visual observation according to CEN (2015) [31] and, if necessary, by pricking with a knife to determine the severity and its progression. Numerical scores were assigned to each sample set after assessment, as suggested by Rapp and Augusta (2004) [24] and described in Table 2. The mean values were used to compare the extent of deterioration for each treatment class for each set. Decay scores were given for the most decayed/infested part of the specimens.

#### 2.7. Monitoring the climate and recording of data

Several studies have already reported that the climate of the test site has a significant impact on wood degradation and subsequent wood decay [32–34] and therefore plays a crucial role in estimating the life span of an outdoor wood product [5]. However, it is very important to mention that most studies have not been able to accurately correlate the effects of macroclimate and wood decay [35,36,37]. The physical degradation of wood is often significantly influenced by climatic factors such as relative humidity, precipitation and ambient temperature. These factors influence the rate of moisture diffusion in wood and lead to the formation of a moisture gradient within the woody biomass, which in turn causes cracks and fissures in the wood surface and favours fungal decay [32]. The climatic data recorded during the study period, therefore, illustrate the influence of environmental conditions on wood degradation. The Dehradun valley is located in the Garhwal region and in the foothills of the Himalayas between the Ganges and Yamuna rivers at an altitude of 437 m. The average rainfall (RF), relative humidity (RH), maximum (max temp) and minimum temperatures (min temp) of Dehradun during the study period were considered for the inferences

**Table 2**  
Numerical ratings assigned to wood specimens based on above ground degradation.

Numerical rating	Condition of specimens
0	Sound
1	Slight Attack
2	Moderate Attack
3	Severe Attack
4	Failure

drawn and discussing the findings. As no sensor-based recording system was available at the test site, as was the case for Žlahtič et al. (2015) [34], the climatic data of the Dehradun valley was recorded from the website of World Weather Online (<https://www.worldweatheronline.com/dehradun-weather/uttarakhand/in.aspx>) for the Dehradun city and used as a reference. It was essential to monitor the climatic factors of the test site as these often indicate the exact time of onset of decay and give an idea of the precursors that led to fungal growth in the exposed specimens. The evaluation period of 30 months was composed of 4 cycles. The study period of each cycle (six months; one year for fourth cycle) was divided so that August to January mainly covered the monsoon and winter seasons and February to July covered the summer and pre-monsoon seasons. This was done to expose the outdoor specimens to successive wetting and drying cycles (Fig. 1), which could promote cracking and serve as a precursor to fungal decay.

### 2.8. Statistical analysis

IBM® SPSS® Version 28 software was used for the statistical analysis. To analyse the data, the mean values of the different treatments were evaluated. A one-way ANOVA was used to analyse the mean values of the treatments. In addition, a Duncan post hoc analysis was performed at  $\alpha = 0.05$  to test for significant differences between treatment means. A Kruskal-Wallis test for independent specimens was also performed to compare the statistical significance of the ranks assigned to the different treatments.

## 3. Results and discussion

All specimens used for each treatment set, with the exception of controls, were subjected to pressure impregnation. The mean retention values obtained for each set are shown in Table 3. The data were subjected to further statistical analysis using SPSS for analysis of variance and post hoc tests, which proved that the MW pretreatment significantly ( $p \leq 0.05$ ) improved the mean retention of the preservative in the treated specimens compared to the control set (CP).

MW treatment resulted in loss in moisture in the range of 11%–14% depending on the MW exposure time. It can be argued that the moisture loss due to MW treatment might have affected the uptake of treating chemicals. In order to normalise the effect of moisture loss, the weight of the specimens prior to MW treatment was used in the calculation of retention and the results have been included in Table 3. Though the

**Table 3**

Retention values ( $\text{kg}/\text{m}^3$ ) exhibited by different sets of specimens before exposure.

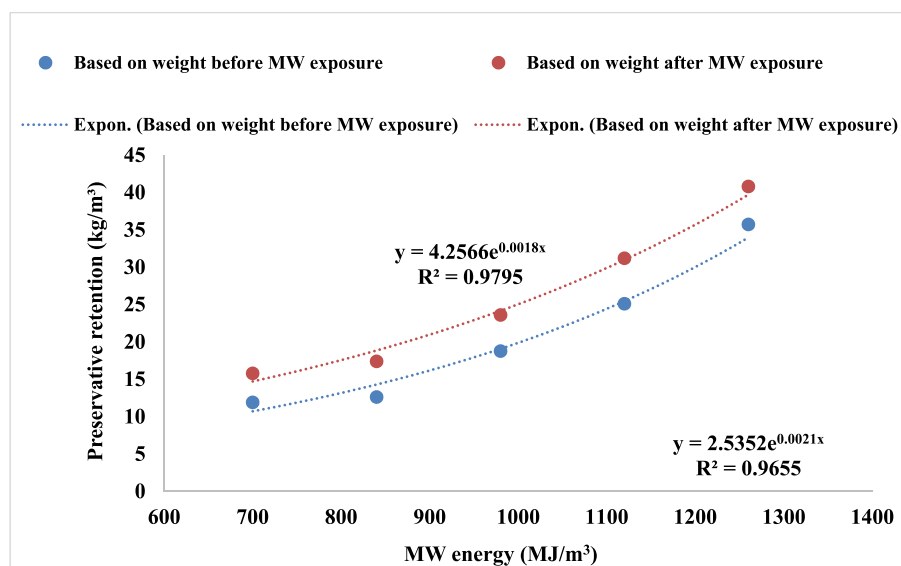
Treatment	WPL (%)	Retention values ( $\text{kg}/\text{m}^3$ ) based on weight after MW	Retention values ( $\text{kg}/\text{m}^3$ ) based on weight before MW
C	–	–	–
CP	–	7.90 <sup>a</sup> ( $\pm 0.28$ )	7.90 <sup>m</sup> ( $\pm 0.28$ )
MW 20	11.52 ( $\pm 0.87$ )	15.82 <sup>b</sup> ( $\pm 0.44$ )	11.91 <sup>n</sup> ( $\pm 0.55$ )
MW 24	12.51 ( $\pm 0.91$ )	17.39 <sup>c</sup> ( $\pm 0.51$ )	12.62 <sup>n</sup> ( $\pm 0.53$ )
MW 28	14.16 ( $\pm 0.74$ )	23.60 <sup>d</sup> ( $\pm 0.32$ )	18.77 <sup>o</sup> ( $\pm 0.35$ )
MW 32	14.17 ( $\pm 0.82$ )	31.22 <sup>e</sup> ( $\pm 0.47$ )	25.12 <sup>p</sup> ( $\pm 0.38$ )
MW 36	14.4 ( $\pm 0.57$ )	40.79 <sup>f</sup> ( $\pm 0.70$ )	35.72 <sup>q</sup> ( $\pm 0.76$ )

Note: Standard errors are presented within parenthesis. The body of the table shows the average values (at  $\pm 95\%$  confidence interval) of 12 replicates per treatment. Equal alphabets in columns indicate no significant difference between treatments, and different alphabets indicate significant difference between treatments according to Duncan's post hoc analysis ( $\alpha = 0.05$ ).

retention values reduced by 3.9–6.1%, Duncan's analysis showed that these values were significantly higher compared to the control set (CP). Further, it is apparent that with the increase in MW treatment time, the retention significantly increased, particularly beyond MW 28.

The results clearly showed that MW pretreatment significantly improved the retention of BBA preservatives, with treated specimens exhibiting about two to five-fold increase in retention compared to untreated controls, which is consistent with the findings of previous researchers [38]. This improvement in retention could be directly related to the structural changes induced by MW irradiation, which increased the permeability of the wood by disrupting the pit membranes and facilitating the penetration of preservative. Loss of moisture as a result of applied MW energy also increased the availability of free space within the wood matrix which also gradually contributed to it retaining more treating chemical. The results are consistent with those of previous researchers [12,39–42] who also reported similar findings after high intensity MW treatment.

To better visualise the effect of MW pretreatment on the preservative retention, the retention values were plotted against applied MW energy, and the result is presented in Fig. 1. Retention values calculated by both the initial weights (before and after MW treatment) have been plotted separately. A strong exponential relation was observed between MW energy and preservative retention with  $R^2$  values ranging from 0.98 to 0.99 (Fig. 1).



**Fig. 1.** Relationship between applied MW energy and preservative retention.

Microwave irradiation of wood primarily supplies electromagnetic energy into the material's polar constituents, predominantly liquid water, converting electromagnetic energy into thermal energy within the bound and free water phases and, to a lesser extent, into the lignocellulosic matrix. As water temperature rises, phase change occurs, and steam is generated inside cells and lumina. A portion of the incident microwave energy is consumed as sensible heating of wood components and latent heat of vaporization; once boiling is reached, continued energy input produces superheated vapor and elevates internal vapor pressure. Localized steam overpressure and rapid volumetric expansion produce mechanical stresses that rupture cell walls and middle lamellae, progressively degrading the wood microstructure. At lower energies heating rates are modest, vapor generation is limited, and internal pressures remain comparatively low resulting in less visible impact of the treatment. At this stage, cell walls experience reversible thermal softening rather than catastrophic failure or hornification, so microstructural integrity remains largely preserved. The result is relatively small moisture loss as observed in this study and may only inflict minor increases in porosity or permeability [18], which together produce limited changes in preservative uptake and retention.

Although MW treatment produced only moderate WPL (approximately 11–14 %), the measured chemical retention of BBA remained high and increased with applied MW energy, especially MW 28 onwards. To determine whether the observed changes in retention are solely a consequence of MW induced WPL or whether MW energy also caused structural or anatomical alterations to an extent that influence uptake and retention, the relationship between WPL, and retention was plotted and examined (Fig. 2) to possibly separate the effects of simple moisture-driven concentration changes from energy-driven modifications of the wood microstructure that could alter permeability, cell-wall accessibility, and reagent fixation. Retention values calculated by both the initial weights (Table 3: Before and after MW treatment), have been plotted separately and it was observed that the relationship between the studied parameters for MW 20 and MW 24 was more or less linear whereas the relationship was exponential for MW 28, MW 32 and MW 36. This ascertains our initial assumption that beyond a threshold limit of applied energy, rapid structural destruction in combination with MW induced WPL was responsible for the observed retention levels in the specimens. With increasing energy input, the rate of vapor formation and localised superheating accelerates, producing higher internal pressures and mechanical shock. This might have caused extensive rupture of cell walls, delamination of middle lamellae and creation of new flow paths [21]. The cumulative damage possibly increases bulk permeability and free-volume available for preservative ingress resulting in the exponential increase as observed in our study (Fig. 1, Table 3). The results of this study confirm the hypothesis that MW pretreatment improves the retention of preservatives which in return may prolong the

outdoor service life of Norway spruce wood. The increase in retention in all MW pretreated specimens have directly resulted in improved durability reported in the later part of this section.

It is noteworthy that the specimens pretreated with higher MW energy levels (MW 28, MW 32, MW 36) showed no visible decay during the study period of 30 months in both outdoor open and shaded environments. The study period of each cycle (six months; one year for cycle 4) was divided so that August to January mainly covered the monsoon and winter seasons and February to July covered the summer and pre-monsoon seasons. This was done to expose the outdoor specimens to successive wetting and drying cycles (Fig. 3), which could promote cracking and serve as a precursor to fungal decay.

The specimens treated with MW, exhibited remarkable resistance even under these unfavourable use conditions (Table 4) whereas, in contrast, the untreated control specimens (C and CP) showed early signs of fungal infestation already from the first cycle itself (Fig. 4 a<sub>1</sub> & b<sub>1</sub>), which continued to deteriorate over time (Fig. 4 a<sub>4</sub> & b<sub>4</sub>). This is in line with earlier studies [5,35], which indicate that increased exposure to moisture accelerates fungal colonisation and decay in untreated wood. The protective effect of MW pretreatment in combination with a suitable preservative system, therefore, indicates that it has the potential of effectively mitigating the effects of environmental stressors (Table 4 and Fig. 3), on the longevity of wood.

All specimens were individually assessed for deterioration using the classification presented in Table 2. To determine the condition of individual treatment groups, the scores received by each specimen were averaged, and the results are presented in Tables 5 and 6 for further analysis. From the ratings it can be inferred that the extent of decay or damage decreased with increasing BBA retention and applied MW energy, indicating a possible synergy. The specimens subjected to higher-intensity MW pretreatment exhibited improved decay resistance compared to untreated wood, likely due to the greater retention of preservatives. Visual inspections confirmed that the treated sets with MW 28, MW 32 and MW 36 showed no signs of decay or damage even after 30 months of exposure in the open, above-ground condition (Fig. 4 e<sub>4</sub>, f<sub>4</sub>, & g<sub>4</sub>). All sets of MW modified specimens exhibited higher durability than the sets of C and CP for both set 1 and set 2 specimens as evident from Tables 5 and 6. Till 30-month exposure limit, no notable difference could be observed between MW treated specimens. However, the results might have been different and clearer had it been exposed for a longer duration and future studies should focus on this aspect.

Table 5 shows that the MW-pretreated specimens showed no visible signs of decay during the first 18 months of outdoor exposure, as no growth of fungal stains and contamination was evident, even after exposure to conditions that favoured rapid fungal growth (Table 4, Fig. 3). However, fungal stains were visible in the bottom layers of both the C and CP specimens for set 1 during the first cycle (Fig. 4; a<sub>1</sub> and b<sub>1</sub>).

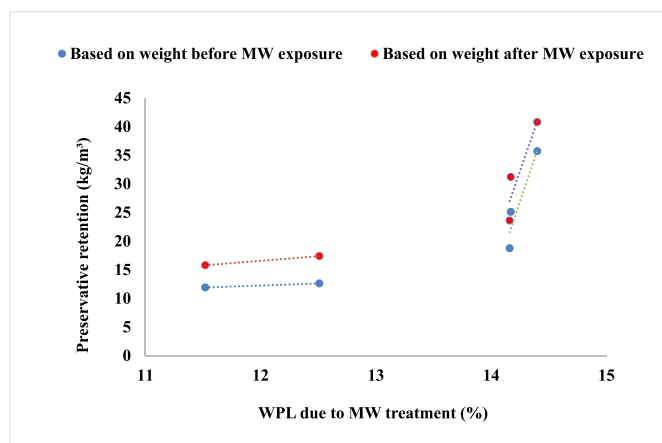


Fig. 2. Relationship between preservative retention and WPL (%).

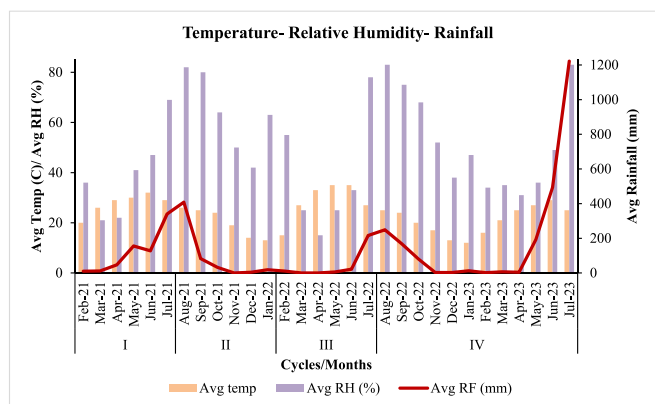


Fig. 3. Combined representation of Average Rainfall (mm), Average Temp (°C) and Relative Humidity during the exposure period.

**Table 4**  
Climatic factors responsible for decay initiation during the study period.

Cycle	Duration (Months)	Average Max temp.	Average Min temp.	Average temp.	Average RF (mm)	No. Of rainy days	Average RF/day (mm)	Average RH (%)	Cloud (%)
I	6	31.7	18.8	27.7	115.4	5.7	17.1	39.3	26.7
II	6	24.3	14.0	20.2	91.0	4.8	20.6	63.5	32.0
III	6	34.8	19.0	28.7	42.5	2.8	8.3	38.5	22.8
IV	12	28.7	15.4	21.2	202.9	8.3	15.2	52.6	29.2

Although MW pretreatment significantly improved preservative retention and durability, some limitations must be considered. For example, the lower MW energy levels (MW 20 and MW 24) did not provide complete resistance to decay, as slight fungal growth was observed. This is in line with our previous correlation analysis, where these two sets did not exhibit an exponential rise in preservative retention. This suggests that there is a threshold value for MW energy (MW 28 in this study) above which the preservative retention and durability significantly improve. Although the study focusses on a single wood species, it would be beneficial to investigate whether similar results can be achieved in other refractory and non-durable wood species, and separately in sapwood and heartwood as well under identical test set up and moisture distribution. Depending on the test statistics of the present research, it can be fairly concluded that the MW pretreatment in combination with BBA was highly capable of protecting the otherwise perishable Norway spruce over a period of 30 months (Fig. 4 c<sub>4</sub>, d<sub>4</sub>, e<sub>4</sub>, f<sub>4</sub>, & g<sub>4</sub>) outdoors where climatic factors were very much in favour of incipient decay and degradation. In the specimens exposed outdoors under the shade, the extent and onset of decay was even slower and quite predictably so. Most of the MW modified specimens remained clear of any visual signs of decay until the 30th month except for the set of MW 20, exposed to the lowest MW energy, where slight initiation of mould growth was initiated after the 3rd cycle and was fairly visible after cycle 4 (Fig. 4 j<sub>4</sub>).

However, the control specimens (C and CP) were severely affected during the study period for both sets; particularly the ones exposed to the outdoor open condition (Fig. 4 a<sub>4</sub> and b<sub>4</sub>), as indicated by the higher numerical decay ratings. The untreated control specimens (C) already showed very early signs of fungal infestation in the first cycle (Fig. 4: a<sub>1</sub>), where patches of mould growing on the surface could be found. Similar observations were made on the specimens that had not been modified with MW but had been treated with preservatives (CP), although at a lesser extent (Fig. 4 b<sub>1</sub>). The upper layers showed signs of photodegradation and natural weathering in the specimens from set 1 and became rough and grey during the course of the study. Cracks and checks were visible on most of the upper layer specimens, formed as a result of the rapid drying and wetting cycles. The lower layers remained moist, indicating efficient moisture entrapment [30], which was ideal for the development of mould and fungal colonisation. Environmental conditions of the test yard played a crucial role in the progression of decay throughout this study, with open outdoor conditions leading to faster fungal colonisation due to direct sunlight, rain and fluctuating humidity.

The specimens kept under shade showed no significant discolouration due to photodegradation (Fig. 4 h<sub>1</sub>-n<sub>1</sub> & h<sub>4</sub>-n<sub>4</sub>) and the extent of cracking on the surface was also significantly less or absent compared to the specimens exposed in open. The specimens treated with MW (Fig. 4 j<sub>1</sub>; k<sub>1</sub>; l<sub>1</sub> & l<sub>4</sub>; m<sub>1</sub> & m<sub>4</sub>; and n<sub>1</sub> & n<sub>4</sub>) showed significantly higher resistance to moulds compared to the untreated controls (Fig. 4: h<sub>1</sub> & h<sub>4</sub>). This highlights the potential of MW pretreatment in producing wood resilient to different environmental and use conditions, making it a robust method for improving the longevity of wood.

The untreated control specimens (C) had the highest mean decay values, with values increasing over time, indicating significant fungal attack and incipient wood decay which is usual for a perishable species. The specimens treated with MW (MW 28, MW 32, MW 36) consistently had the lowest decay values, with a median value of 0, confirming their

resilience. MW 20 and MW 24 had slightly higher decay scores, but were still significantly lower than the controls, suggesting that lower MW energy levels may offer some protection initially, but may not be entirely sufficient for long-term protection as the retention values were significantly lower. The statistical analysis confirms that MW pretreatment significantly increases the durability of Norway spruce wood in outdoor conditions by increasing preservative retention and reducing susceptibility to fungi. The numerical ratings obtained in the different cycles (Tables 5 and 6) were further statistically analysed using the Kruskal-Wallis test for independent specimens to check the significance of the results (Figs. 5 and 6).

The above analysis (Figs. 5 and 6) statistically establishes the enhanced durability of MW modified wood with comparison to the control specimens. MW modified specimens performed significantly better than the untreated control, whereas untreated controls and MW non modified controls treated with preservatives (C and CP respectively) exhibited statistical similarity in terms of scores assigned for both treatment sets. The Kruskal-Wallis test was used to determine whether the numerical decay scores for wood specimens exposed in outdoor open conditions assigned to different treatment groups (Set 1) were significantly different. The values of the test statistic for comparisons between MW treated specimens with higher applied energy (MW 28, MW 32, MW 36) and the untreated control (C) were all 15.125 with a standard error of 4.933. The standardised test statistic of 3.066 and the significance value of 0.002 indicate a highly significant difference in decay resistance. After adjusting for multiple comparisons, the adjusted significance remains at 0.046, which statistically confirms the durability improvement of Norway spruce wood in open outdoor conditions.

The results of the Kruskal-Wallis test for wood specimens exposed under shade conditions (set 2) is presented in Fig. 6. The values of the test statistic for the comparisons between the MW-treated specimens (MW 24, MW 28, MW 32, MW 36) and the untreated control (C) were all 14.000 with a standard error of 4.603. The standardised test statistic of 3.042 and the significance value of 0.002 again indicate a strong statistical difference between the MW-treated specimens and the untreated controls. The adjusted significance remains at 0.049, confirming that the MW pretreatment significantly improves durability under shaded conditions as well where fungal growth is generally slower. Compared to Set 1, the slightly lower values of the test statistics indicate that decay was generally less severe under shaded conditions, but the MW-treated specimens still showed a significantly better durability. The findings could emphasise the effectiveness of MW pretreatment in environments with controlled climatic stressors like lower UV exposure and humidity fluctuations. The control specimens (C) showed moderate levels of decay, with an increasing trend over time. MW-treated specimens (MW 24, MW 28, MW 32, MW 36) showed significantly lower decay values, with MW 32 and MW 36 showing a mean decay value of 0 throughout the study. The MW 20 specimens showed minor fungal growth (Fig. 4 j<sub>4</sub>), similar to what was observed in set 1, suggesting that lower MW energy levels provide some protection but may not be enough to completely prevent fungal infestation even if used under shade.

The statistical analyses also provide strong evidence that higher MW energy levels, in particular MW 28, MW 32 and MW 36, were able to reduce modified wood's susceptibility for biodeterioration as those treatments consistently showed no visible decay (numerical rating = 0) after 30 months exposure outdoors, both in the open and under the

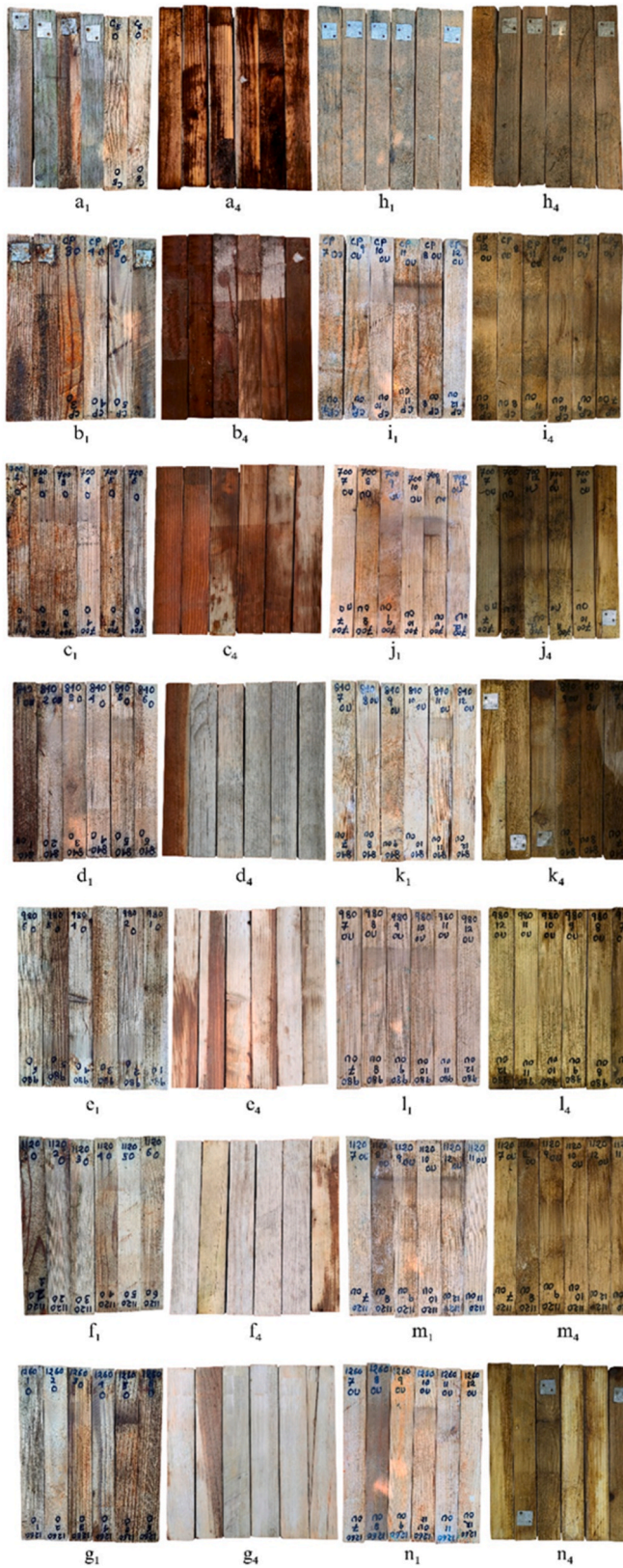


Fig. 4. Appearance of test specimens exposed outdoors (Open and Under shade) after exposure of 30 months (Cycle 1 and Cycle 4) (a<sub>1</sub>-g<sub>1</sub> & h<sub>1</sub>-n<sub>1</sub>: Cycle 1 Outdoor Open & Cycle 1 Under Shade; a<sub>4</sub>-g<sub>4</sub> & h<sub>4</sub>-n<sub>4</sub>: Cycle 4 Outdoor Open & Cycle 4 Under Shade; a & h = C, b & i = CP, c & j = MW 20, d & k = MW 24, e & l = MW 28, f & m = MW 32, g & n = MW 36).

Table 5

Mean numerical ratings given to the set of specimens during 30 months of exposure with standard deviation values in parenthesis (Outdoor Open); lower the score, better the performance.

Sample	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	Mean Rating
C	1 (±0.81)	1 (±0.81)	2 (±0.58)	3 (±0.68)	1.75 (±0.83)
CP	1 (±0.57)	1 (±0.57)	1 (±0.57)	2 (±0.38)	1.25 (±0.43)
MW 20	0	0	0	1 (±0.89)	0.25 (±0.43)
MW 24	0	0	0	1 (±0.68)	0.25 (±0.43)
MW 28	0	0	0	0	0
MW 32	0	0	0	0	0
MW 36	0	0	0	0	0

Table 6

Mean numerical ratings given to the set of specimens during 30 months of exposure with standard deviation values in parenthesis (Outdoor Under shade); lower the score, better the performance.

Sample	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle	Mean Rating
C	1 (±0.00)	1 (±0.00)	1 (±0.00)	2 (±0.37)	1.25 (±0.43)
CP	0	1 (±0.37)	1 (±0.37)	2 (±0.00)	1.00 (±0.70)
MW 20	0	0	0	1 (±0.81)	0.25 (±0.43)
MW 24	0	0	0	0	0
MW 28	0	0	0	0	0
MW 32	0	0	0	0	0
MW 36	0	0	0	0	0

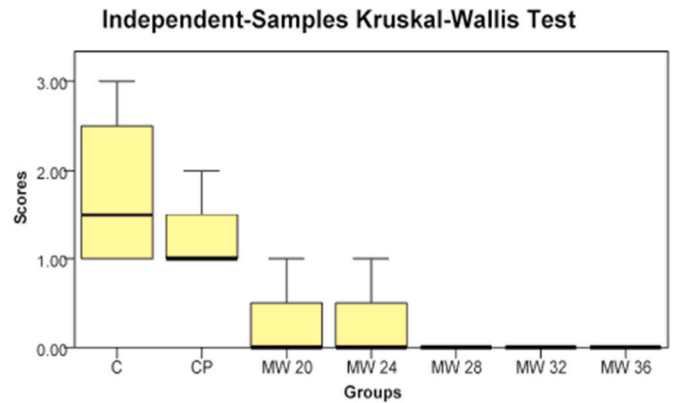


Fig. 5. Box plot representation and test statistics of Outdoor open specimens sets (Set 1) showing significant difference in scores after Kruskal Wallis; lower the score, better the result.

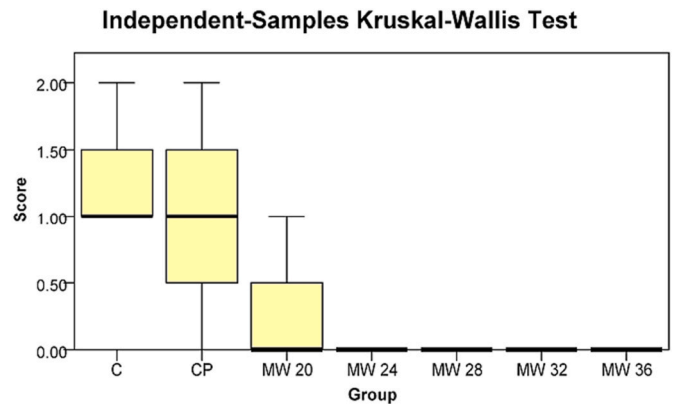


Fig. 6. Box plot representation and test statistics of Outdoor under shade specimens sets (Set 2) showing significant difference in scores after Kruskal Wallis; lower the score, better the result.

shade. The study also highlights that MW pretreatment outperforms conventional preservation methods in terms of durability improvement. The control specimens treated with preservatives but without MW pretreatment (CP) showed signs of fungal attack over time, suggesting that the application of conventional preservatives alone does not provide sufficient long-term protection to perishable wood and other modification techniques like MW pretreatment of thermal modification should be used mutually to obtain better result. MW combined with preservative treatment significantly improved the effectiveness of the preservative solution, potentially indicating a reduction of reliance on high chemical doses and providing a more environmentally friendly approach to sustainable wood preservation.

The observed increase in durability was likely due to both physical and chemical modifications in the MW-treated wood. Previous research has shown that MW irradiation alters the structure of wood cell walls by increasing permeability and potentially modifying the chemical composition of lignocellulosic polymers [18,38,42]. Here, in the study the retention of BBA was increased by a factor of 2–5 folds which could be the most important reason for the enhanced durability of MW modified wood specimens. Alongside the same, the changes in the structure of the chief polymeric constituents after MW pretreatment in wood might have played some important role as was highlighted by Xing et al. (2023) [43]. Increased crystallinity of MW modified wood was reported by Xing et al. (2023) [43] which might have resulted in the modified wood becoming more hydrophobic in nature [44]. Hydrophobic nature of wood makes it more dimensionally stable under atmospheric pressure and reduces its interaction with surrounding moisture making it less susceptible to fungal attack. An important observation in the study could be the threshold effect of the applied MW energy levels on the durability of the wood. While MW 20 and MW 24 provided some resistance to decay, they were not as effective as higher energy treatments. Fungal growth was observed in the specimens treated with MW 20 after 18 months, suggesting that there is a minimum threshold of energy required for optimal improvement in durability. The observation is in line with [43] where impact of higher energies of MW was studied for impactful changes in the chemical composition of wood which might have inflicted positive changes in its resistance to biological decay, coupled with enhanced preservative loading, as observed in our study.

Xing et al. (2023) [43] reported an increase in relative lignin content in MW-treated wood, where 3.5 % and 8.5 % increase respectively in sapwood and heartwood lignin content was reported, which could also contribute to the improved durability observed in our study. The authors concluded that this was primarily due to the concurrent occurrence of MW and hydrothermal modification in wood which produces a large number of free radicals resulting in cross linking and increasing the relative lignin content [45]. The role of lignin in antifungal activities is well discussed and researched [46] over the years and might well be the case of enhanced protection against wood destroying microorganisms in this study. Microwaves also promote the reorganization of cellulose molecular chains in wood [47] which increase crystallinity of cellulose and dramatically decreases its relative quantity. This, coupled with the reduction in the overall holocellulose content [43] can also make wood unrecognizable as a food source to the decaying agents resulting in higher durability. The reduction in holocellulose content may also play a role by making the wood less susceptible to enzymatic degradation by decay fungi. The findings of this study have significant implications for the wood preservation industry. MW pretreatment offers a promising, and sustainable approach to improving the service life of Norway spruce, reducing the need for frequent reapplications of chemical preservatives. This has important environmental and economic implications as it could minimize the use of potentially harmful chemicals when used in conjugation. The enhanced preservative retention also indicates that lower concentrations of chemicals could be used while maintaining effectiveness, thereby reducing environmental impact. Future research should focus on optimizing MW pretreatment parameters to balance

improved permeability with minimal adverse effects on wood strength. Additionally, long-term field trials in different climatic regions would provide further validation of MW pretreatment as a viable commercial wood modification technique.

#### 4. Conclusion

It was observed in this study that the BBA retention value increased from around 8 kg/m<sup>3</sup> in MW untreated spruce wood to over 40 kg/m<sup>3</sup> in wood that was before impregnation treated with microwaves of the applied MW energy of 1260 MJ/m<sup>3</sup>. So, this study shows that MW pretreatment is an effective method to improve the uptake of wood preservatives and the durability of Norway spruce wood, which is known to be difficult to treat with preservatives due to the presence of aspirated pits. The synergy of increased preservative retention, structural changes and resistance to environmental damage induced by MW, emphasises the potential of MW pretreatment as a sustainable wood preservation technology. MW pretreatment of Norway spruce wood, in the present research has highlighted its transformative potential in improving preservative uptake and durability of treated wood for outdoor use. Possible changes in the wood microstructure after microwave irradiation and progressive WPL facilitated better uptake and uniform distribution of the preservative, leading to improved protection, especially in wood species with low natural permeability, contributing to more durable and sustainable material. In addition, the chemical changes in the structure of the microwave-treated wood, which was reported in recent literature may have reduced its susceptibility to moisture, which in turn contributes to its outdoor durability. These results suggest that microwave pretreatment could be a promising and eco-friendly method to extend the service life of otherwise perishable Norway spruce wood, reduce maintenance costs associated with its processing and promote sustainable forestry practises. In addition, MW pretreatment could support the development of innovative conservation strategies that are consistent with environmental regulations and sustainability goals. Future studies should explore optimization of treatment parameters for maintaining mechanical integrity and study the long-term effects on MW-modified wood in different climates to assess the economic feasibility on an industrial scale. Another important point worth considering will be moisture equilibration post MW pretreatment to optimize impregnation efficiency, which was not addressed in the present work. The integration of MW treatment with other environmentally friendly wood modification processes should also be explored which could lead to even greater benefits in terms of durability and sustainability, further enhancing the role of MW treatment in the advancement of modern wood research and conservation practices.

#### CRediT authorship contribution statement

**Sauradipta Ganguly:** Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Sanjeet Kumar Hom:** Visualization, Methodology, Formal analysis, Data curation. **Anil Kumar Sethy:** Writing – review & editing, Validation, Formal analysis. **Sanmitra Dan:** Writing – original draft. **Biswajit Debnath:** Visualization, Investigation. **Varun Sharma:** Writing – review & editing, Visualization, Investigation. **Sadhna Tripathi:** Supervision, Project administration, Methodology, Conceptualization. **Davor Kržišnik:** Writing – review & editing, Validation. **Marko Petrić:** Writing – review & editing, Validation.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Data availability

Data will be made available on request.

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