

CHEMICAL MIGRATION AND REDISTRIBUTION OF CCA COMPONENTS IN *EUCALYPTUS NITENS* HEARTWOOD: IMPLICATIONS FOR DURABILITY UNDER ACCELERATED WEATHERING

Juan Roberto Vargas, Luis Yermán, Kyra C Wood, Tripti Singh

ABSTRACT: Chromated copper arsenate (CCA) remains a widely used wood preservative despite regulatory restrictions in regions like Europe. Its protective efficacy stems from chromium binding with wood fibres, which stabilizes copper and arsenic, reducing leachability. However, low levels of CCA components remain mobile under wet conditions, potentially inhibiting fungal growth in untreated wood exposed through surface checks. This phenomenon has been observed in softwoods with shallow preservative barriers, particularly in North American species such as spruce, pine, and fir, which have impermeable heartwood. This study investigated whether a similar protective effect occurs in hardwoods by examining CCA migration in *Eucalyptus nitens* subjected to ten repeated wet/dry cycles simulating outdoor exposure. Arsenic exhibited the highest leaching rate (22.8%), while copper (8.7%) and chromium (1.4%) remained more stable. Peak leaching occurred within the first four cycles before stabilizing. Despite observable copper migration into surface checks, the concentrations achieved were insufficient to provide meaningful secondary protection against fungal colonisation. These findings highlight the limitations of preservative mobility in hardwoods and suggest the need for alternative treatment strategies, such as deeper preservative penetration or modified formulations, to improve the durability of *E. nitens* in above-ground applications.

KEYWORDS: Chromated copper arsenate, metal migration, *Eucalyptus nitens*, preservative leaching, timber durability

1 – INTRODUCTION

CCA fixation occurs through the reduction of Cr (VI) to Cr (III), forming insoluble complexes with Cu and As. Despite this stabilization, low levels of CCA components can still migrate over time, particularly As and, to a lesser extent, Cu and Cr [1]. The extent of this migration depends on wood species, preservative retention, specimen dimensions, and environmental exposure conditions [2]. While some mobility is advantageous for extending protection against fungal and insect attack, excessive migration can compromise preservative efficacy and raise environmental concerns. Previous research has focused predominantly on softwoods, as they are widely used in exterior applications and exhibit relatively simple cellular structures composed of tracheids and parenchyma cells, with higher lignin content [3, 4]. Studies on CCA-treated *Pinus spp.* indicate that metal migration is typically low, even under wet/dry cycling designed to simulate outdoor weathering conditions [2, 5-8]. Unlike softwoods, hardwoods present significant challenges for preservative treatment due to their complex cellular structure, including vessels and fibres, which often exhibit poor preservative penetration. While some hardwoods contain treatable parenchyma cells, the refractory nature of fibres can result in uneven preservative distribution and poor long-term performance, particularly in soil contact applications [9,

10]. Additionally, extractives in hardwood heartwood may interact with CCA components, affecting fixation efficiency and increasing leachability [11, 12].

One such hardwood of interest is *Eucalyptus nitens* (shining gum), a fast-growing species extensively planted in Tasmania since the 1990s. Originally cultivated for pulp and paper production, market shifts have increased interest in its use for high-value solid wood applications [13-15]. However, short-rotation plantation management has resulted in timber with large knots, high shrinkage rates, and inherent growth stresses [14], making it prone to dimensional instability. Despite these limitations, *E. nitens* presents a viable resource for structural timber, provided it can be effectively treated for durability.

Nonetheless, *E. nitens* heartwood lacks natural durability against fungal decay and termites, necessitating preservative treatment or chemical modification for reliable performance in exterior applications [16].

The highly refractory nature of its heartwood limits preservative uptake, making it challenging to meet standard penetration requirements [17]. Wood et al. (2022a) demonstrated that *E. nitens* heartwood often fails to meet the minimum 5 mm penetration depth required under Australian/New Zealand Standard AS/NZS 1604.1 [18]. Similarly, Vargas et al. (2023) found that treatment depths below 5 mm were insufficient to protect *E. nitens* heartwood from fungal decay in laboratory conditions.

Juan Vargas, National Centre for Timber Durability and Design Life, University of the Sunshine Coast, Dutton Park, Queensland, Australia, jrv015@student.usc.edu.au

Tripti Singh, National Centre for Timber Durability and Design Life, University of the Sunshine Coast, Dutton Park, Queensland, Australia, tsingh1@usc.edu.au

Luis Yermán, School of Civil Engineering, The University of Queensland, Brisbane, Australia, l.yerman@uq.edu.au

Kyra Wood, Centre for Sustainable Architecture with Wood, University of Tasmania, Newnham Campus, Tasmania, Australia, kyra.wood@utas.edu.au

These findings suggest that while *E. nitens* has potential for exterior applications, alternative treatment methods or modifications may be required to achieve adequate preservative retention and penetration [19]. In addition to treatment limitations, *E. nitens* is highly susceptible to check formation when subjected to repeated wet/dry cycles. While all woods experience checking to some extent, some hardwoods are particularly prone to this phenomenon [14, 20]. These surface checks can extend beyond the preservative treatment depth, exposing untreated inner wood to fungal colonization.

Studies on CCA-treated softwoods have demonstrated that mobile CCA components can redistribute into surface checks, creating a secondary protective barrier against fungal attack [1, 21]. This "barrier mobility effect" has been well documented in softwoods under North American outdoor exposures, where copper concentrations in checks of CCA-treated decking increased over time, reaching 0.29 mg Cu/g of wood after five months and 0.35 mg Cu/g after one year [1]. While these concentrations were below the fungitoxic threshold for established fungal mycelium, they successfully inhibited spore germination, including that of copper-tolerant fungi [22]. Additional long-term field studies on shallow-treated softwood decking in Australia have further supported the protective role of preservative mobility, even where penetration is limited [23].

These findings highlight the potential value of preservative mobility in extending the service life of treated wood. However, whether similar protective benefits occur in hardwoods such as *E. nitens* remains unclear due to differences in wood chemistry, cellular structure, and extractive composition.

2 – EXPERIMENTAL SETUP

2.1 SAMPLE PREPARATION

Untreated 26-year-old *E. nitens* boards were crosscut into seventy wafers (2 mm thick, approximately 25 mm × 25 mm) and sanded to achieve uniform thickness. The wafers were oven-dried to a constant mass at 50°C and weighed to the nearest 0.001 g. Additionally, larger 80 mm × 97 mm × 13 mm boards were prepared, similarly oven-dried at 50 °C, and weighed to establish baseline mass measurements. Based on the findings of Vargas et al. (2023), where preservative redistribution in the checks was negligible at the standard H3 retention level (0.38% m/m CCA), the preservative retention in this study was intentionally increased to achieve a higher concentration, approaching the H4 target level, according with Australian/New Zealand Standard AS/NZS 1604.1 [18]. The wafers were immersed in a 2 % CCA solution (by total metal weight) and subjected to a vacuum treatment at -70 kPa for one hour to facilitate preservative uptake. After vacuum release, the wafers remained submerged for an additional 30 minutes before being blotted, dried, and reweighed to determine net solution absorption. The treated wafers were stored for 24 hours at ambient

temperature under cover to minimize drying, allowing fixation to occur, and were then oven-dried at 50°C to a stable weight. To verify retention levels, twenty wafers were randomly selected, ground to pass a 20-mesh screen, and the resulting sawdust was analysed for Cu, Cr, and As using X-ray fluorescence spectroscopy (XRF) with a Hitachi X-Supreme8000 series XRF analyser. The analysis followed the American Wood Protection Association Standard (AWPA) A9 [24], with detection limits calibrated to 10 ppm for all analysed metals.

2.2 FORMATION OF CHECKS AND WEATHERING

Thirty untreated boards (80 mm × 97 mm × 13 mm) were subjected to a simulated controlled rainfall to evaluate check formation and preservative migration. A custom-built rainfall apparatus was used to replicate outdoor exposure, delivering rainfall at 6.4 mm/h through a nozzle system connected to a pump. The apparatus was calibrated to ensure even water distribution, with nozzles positioned 60 cm above the wood samples, which were placed in aluminium foil trays (22 cm x 15.7 cm x 4.7 cm) inclined at 5° to facilitate runoff. Samples were elevated 50 mm above the tray bottoms to prevent direct contact with pooled water.

The wet/dry cycle protocol involved watering for two minutes every two hours over a 20-hour period (equivalent to 64 mm/day) followed by oven-drying at 60°C for 24 hours, completing one full cycle. Samples underwent ten cycles (20 days) before the longest check in each sample was analysed. Check dimensions (length, width, depth) were measured using feeler gauges, where depth was recorded at the deepest point along the check length, and width was recorded at the widest point along the check length.

In this study, 13 mm thick boards were used based on prior research which examined the effects of board thickness (12, 19, and 25 mm) on crack development and water uptake in ACQ-treated *E. nitens* [20]. The results indicated that 12 mm boards developed a significantly higher number of cracks, which were also larger in width, depth, and length, compared to thicker samples.

To assess CCA migration into surface checks, CCA-treated wafers were positioned along the checks, simulating preservative redistribution in a controlled laboratory setting. Three randomly selected wafers were split lengthwise and attached to both sides of the longest check in each weathered board using a two-part epoxy adhesive, ensuring that adhesive application remained away from the check to prevent interference with metal diffusion pathways.

This setup replicated tangential check formation, where cracks ran parallel to the grain rather than across it (radial orientation) (Fig. 1). This distinction was crucial, as grain orientation affects moisture absorption, stress distribution, and preservative retention in timber

structures. Preservative redistribution was assessed by subjecting samples to an additional ten wet/dry cycles. The likelihood of preservative migration into the checks was maximised by carefully positioning the samples so that rainfall directly impacted the check during each cycle, ensuring consistent exposure to moisture-driven diffusion. This approach was chosen to simulate real-world outdoor conditions, where preservative-treated timber in decking, cladding, and exposed structural elements may develop surface checks over time due to cyclical swelling and shrinkage. Leachate samples were collected periodically throughout the weathering cycles, according to the following scheme:

Cycles 1 and 2: Separate samples were collected after each event for the first six rainfall events in each cycle, then a single cumulative sample was taken to cover rainfall events seven through ten for each cycle.

Cycles 3 and 4: Individual samples were collected after each of the first five rainfall events in each cycle, then a cumulative sample was collected for the remaining rainfall events.

Cycle 5: Individual samples were collected after each of the first four rainfall events, then a cumulative sample was taken for the remaining events.

Cycles 6 and 7: Separate samples were collected after each of the first three rainfall events per cycle, followed by a cumulative sample for events four to ten.

Cycles 8 through 10: In each cycle, an individual sample was collected after the first rainfall event only. After that, a single cumulative sample was collected to cover events two through ten.

Trays were emptied and repositioned to minimize cross-contamination after each collection and ensure consistency in subsequent rainfall events. A 10 mL aliquot was retained from each collection for chemical analysis.

2.3 CHEMICAL ANALYSIS

Aliquots were acidified with 1 mL of 1 M nitric acid prior to analysis to solubilise metal ions. The total concentrations of Cu, Cr, and As in the leachates were quantified using inductively coupled plasma optical emission spectrometry (ICP-OES) (Thermo Fisher iCap Pro). The method detection limits were 5.0 µg/L for As, 1.0 µg/L for Cr, and 1.5 µg/L for Cu.

CCA component migration into surface checks was assessed by splitting the boards lengthwise along the check lines, and dividing each check surface into three sections, corresponding to different vertical positions on the board. In Fig. 2, these sections are labelled as Section 1 (near the top of the incline), Section 2 (middle), and Section 3 (near the bottom). A 1 mm thick slice was then excised from each section along both the height and length of the check to obtain sufficient wood material for analysis (200 mg per sample). The collected wood samples were ground, digested in nitric acid, and

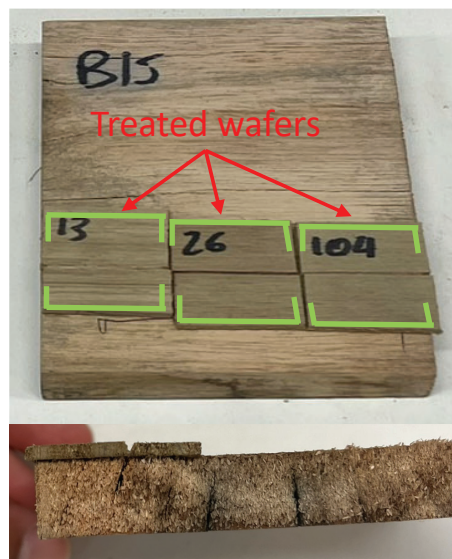


Figure 1. Top and end-grain views of a test assembly with CCA-treated wafers epoxied over a checked board. Green areas indicate glue placement.

analysed via ICP-OES, following the same protocol used for leachate analysis.

2.4 DATA ANALYSIS

The total quantity of leached metals was normalized by surface area to facilitate direct comparison with findings from previous studies. Metal concentrations on the check surfaces were measured before and after weathering, and the data were subjected to an analysis of variance ($\alpha = 0.05$) to determine statistical differences in preservative retention and migration patterns.

3 – RESULTS

3.1 CHEMICAL TREATMENT AND LEACHING

Cu penetration into the wafers was confirmed by spraying the split surfaces with PAN (1-(2-Pyridylazo)-2-naphthol), a metal indicator that forms intense red- or magenta-coloured complexes with transition metals, particularly Cu. This colorimetric test demonstrated that Cu had completely diffused through the wafers. X-ray fluorescence (XRF) analysis quantified preservative retention, with average concentrations of 0.102% Cu, 0.302% Cr, and 0.157% As (m/m), resulting in a total CCA retention of 0.56% (m/m)—exceeding the H3 hazard class target retention (0.38% m/m) specified in AS/NZS 1604.1 [18]. Cr and Cu levels in the distilled water used for rainfall events were 0.009 ppm and 0.002 ppm, respectively, while As was below the detection limit. These background concentrations were subtracted from the runoff water analyses to ensure accurate quantification of metal leaching. Each experimental assembly comprised one untreated board with three CCA-treated wafers positioned on top (Fig. 1). The total

metal contents per assembly averaged 2.39 mg Cu, 7.10 mg Cr, and 3.68 mg As, providing a benchmark for evaluating CCA redistribution under simulated weathering conditions. Over 23% of the initial As in the wafers was lost over the 10 wet/dry cycles (**Table 1**). In comparison, Cu migration was significantly lower, with 8.7% leached, while only 1.4 % of the Cr was lost. These results align with previous studies across various wood species, demonstrating a consistent trend in CCA component mobility [1, 2, 25]. The differential leaching pattern reflected the higher solubility of As complexes in aqueous environments and the stronger fixation of Cr and Cu within the wood matrix, reinforcing existing knowledge on CCA leaching behaviour under weathering conditions.

The percentages of each element lost per cycle, are presented in **Table 2**. Distinct leaching patterns were observed among the three metals, with As exhibiting the highest mobility, followed by Cu, while Cr showed the least mobility. As leaching peaked during the first four cycles, reaching values above 16% in Cycle 2, while Cu and Cr exhibited lower but still significant release rates. This suggests that more As was available for leaching upon initial exposure to moisture. In contrast, Cu and Cr showed more gradual release trends, with Cu leaching peaking in Cycle 4 (15.1%) and Cr following a similar but less pronounced pattern. These findings align with previous studies indicating that As is the least chemically fixed component in CCA-treated wood, making it more prone to leaching during early exposure periods [2, 26]. The initial phase of leaching was likely associated with more weakly bound preservative components or of those positioned near the wood surface, making them highly susceptible to early loss [2, 27].

In contrast, a portion of mobile Cu may migrate deeper into the wood matrix, where it can bind to reactive sites within the cellular structure. This redistribution may contribute to extended fungal protection, as Cu retained in the wood interior remains biologically active over time [1, 2, 6, 27]. Leaching rates declined after Cycle 5 across all three metals, indicating the depletion of the most readily available preservative fractions. The cumulative leaching trends confirm that As was the dominant leached component, whereas the lower cumulative loss of Cr reinforces its role as a fixation agent.

The reduced mobility of Cu and Cr suggests that some degree of fungal protection remains, but the imbalance in preservative retention may compromise the wood overall durability. **Table 2** additionally presents the leached quantities of Cu, Cr, and As per exposed surface area. The unit micrograms per square centimetre quantifies the amount of preservative metal (Cu, Cr, or As) leached per unit of exposed wood surface. This standardized measurement facilitated direct comparison across studies and treatment conditions by accounting for differences in sample size and exposure surface area.



Figure 2. Sample showing check surfaces split for shavings collection and chemical analysis.

This metric is critical for evaluating the extent of preservative loss and its implications for wood durability and environmental impact. Lower values indicate strong preservative retention, contributing to longer-term protection, while higher values suggest greater leaching, potentially compromising resistance to decay and insect attack. Leaching rates for all three metals stabilized after the fourth cycle, with cumulative losses remaining below 13% from Cycles 5 to 10. Both Cu and As exhibited the most rapid declines, indicating a progressive depletion of readily leachable fractions, while Cr showed a more gradual reduction over the cycles. The highest leaching rates for all elements were observed in Cycle 4, marking a critical threshold where cumulative preservative loss reached 50%. Beyond this point, leaching rates for Cu, Cr, and As began to stabilize, signifying the transition from rapid early-stage depletion to a more gradual and sustained leaching phase.

Table 3 presents a comparison of cumulative metal leaching per surface area with data from previous studies. Since most prior research has primarily examined CCA leaching rates, comparisons for other wood preservatives were based on their respective Cu leaching levels. The exposure conditions in these studies varied, including simulated rainfall, outdoor weathering, atomizer sprays, and full immersion, as outlined in AWWA E11 [28]. Simulated rainfall studies typically spanned four weeks, while outdoor exposure trials ranged from six months to two years, reflecting the variability in test durations and environmental conditions. Our findings indicate that As exhibited the highest cumulative loss, while Cu and Cr showed substantially lower total leaching values. When compared to outdoor exposure studies on CCA-treated wood, such as those by Taylor & Cooper [5] and Lebow et al. [2, 8], the arsenic leaching observed in this study was within the expected range but still lower than some long-term field trials. For instance, Kennedy & Collins [29] reported As losses of 60.0 $\mu\text{g}/\text{cm}^2$ over a one year outdoor exposure, indicating that prolonged weathering may lead to greater cumulative depletion of As from treated wood.

Table 1. Concentration and mass values of copper, chromium, and arsenic in assemblies, before and after repeated wet/dry cycles.

Initial values									
Treated wafers				Untreated wood/ Check			Water		
	Cu	Cr	As	Cu	Cr	As	Cu	Cr	As
ppm	1017.2	3024.6	1570.1	47.1	21.1	24.5	0.002	0.009	0.000
mg	2.39	7.10	3.68	0.047	0.021	0.024	0.022	0.091	0.000
Final values									
Treated wafers				Check surfaces			Leachates		
	Cu	Cr	As	Cu	Cr	As	Cu	Cr	As
ppm	912.7	3026.9	1211.3	107.4	26.3	25.4	*	*	*
mg	2.14	7.10	2.84	0.106	0.026	0.025	0.207	0.101	0.841

* Final values are a total cumulative of the leachates

Interestingly, the simulated rainfall conditions used in this study produced lower total Cu and Cr losses than those reported by Lebow et al. [2, 8] for similar exposure methods. The simulated rainfall rate of 6.4 mm/h, while considered heavy for laboratory conditions, was the minimum rate that the apparatus could consistently dispense. The total rainfall over the 10-cycle testing period was 640 mm, closely aligning with the annual average precipitation in Australia (596 mm) and Queensland (768 mm) and falling within the precipitation range observed across North America (Canada: 524 mm; US: 802 mm) [30-32]. These figures suggest that the accelerated weathering protocol effectively replicated approximately one year of natural exposure in terms of moisture cycling. However, this simulation did not incorporate additional environmental factors such as UV degradation, temperature fluctuations, or biological colonization, which may significantly impact timber performance in real-world conditions.

The majority of previous studies on CCA leaching and fixation have focused on softwoods, with alder (a hardwood) being a notable exception in the work of Temiz et al. [6]. Softwoods typically contain higher lignin concentrations than hardwoods, and their G-lignin structure includes a greater proportion of free phenyl OH groups, which act as primary reaction sites for CCA components [6, 33]. Pizzi and colleagues demonstrated that both lignin content and composition significantly influenced CCA fixation rates and long-term retention, ultimately leading to differences in preservative efficacy between softwoods and hardwoods [34-36]. While hardwoods tend to exhibit better short-term absorption and faster fixation rates than softwoods [12], multiple studies have consistently shown that CCA preservatives are less effectively fixed in hardwoods, leading to higher leaching rates over time [33, 37, 38]. The higher leaching rates observed in hardwoods are largely attributed to their elevated xylan content in hemicellulose, which is more prone to decomposition and leaching than cellulose- or

glucan-rich hemicelluloses. This structural characteristic leads to greater variability in preservative retention over time [39]. Furthermore, leaching studies by Stevanovic-Janezic [37] indicate that rapid Cr reduction, potentially influenced by the high extractive content in cell lumens, contributes to the formation of unstable CCA fixation products. This instability is particularly concerning for As retention, as it results in reduced resistance to As leaching, further compromising the long-term effectiveness of CCA-treated hardwoods.

Accelerated preservative losses in structural applications could compromise wood integrity, potentially leading to faster degradation and reduced load-bearing capacity over time. Unlike softwoods, where even shallow preservative treatments can provide extended protection due to preservative mobility, hardwoods may require deeper preservative penetration or modified preservative formulations to enhance resistance to leaching and environmental exposure. Despite the structural differences and variations in fixation rates between hardwoods and softwoods, CCA-treated wood generally demonstrates low leachability and strong preservative retention. This is in contrast to alkaline copper-based preservative systems, such as alkaline or micronised copper quaternary or azole (ACQ/MCQ/MCA), where Cu migration rates are approximately seven times higher than those observed in CCA-treated wood [27, 40].

This suggests that CCA remains more resistant to leaching than newer copper-based preservatives, but its performance in refractory hardwoods may be limited by insufficient penetration and retention. Furthermore, regulatory restrictions on CCA in many regions have led to a shift toward alternative copper preservatives, that exhibit varying degrees of effectiveness in hardwoods, with differences in fixation, leach resistance, and overall preservative performance, highlighting the need for further research to optimize the application in structural and above-ground hardwood treatments.

Table 2. Average amount of metals leached per unit area and percentage of metals leached per cycle from CCA treated *E. nitens* wafers.

	Quantity leached per unit area (ug/cm ²)						% leached per cycle		
	<i>Cu</i>		<i>Cr</i>		<i>As</i>		<i>Cu</i>	<i>Cr</i>	<i>As</i>
CYCLE 1	1.5	(0.003)	0.6	(0.002)	4.8	(0.015)	14.4	11.9	11.6
CYCLE 2	1.3	(0.002)	0.5	(0.001)	6.9	(0.016)	13.1	10.9	16.7
CYCLE 3	1.0	(0.004)	0.5	(0.002)	4.8	(0.018)	9.6	9.4	11.6
CYCLE 4	1.5	(0.010)	0.7	(0.005)	5.5	(0.034)	15.1	13.6	13.4
CYCLE 5	1.0	(0.005)	0.6	(0.004)	5.3	(0.036)	9.8	11.6	12.7
CYCLE 6	1.1	(0.006)	0.6	(0.004)	4.3	(0.028)	10.6	12.2	10.3
CYCLE 7	0.7	(0.004)	0.5	(0.004)	3.2	(0.025)	7.0	10.0	7.8
CYCLE 8	0.9	(0.003)	0.3	(0.003)	1.8	(0.014)	8.9	6.6	4.3
CYCLE 9	0.6	(0.004)	0.3	(0.003)	2.0	(0.016)	5.4	5.8	4.8
CYCLE 10	0.6	(0.005)	0.4	(0.004)	2.8	(0.026)	6.1	7.9	6.8
Total	10.2		5.0		41.4				

Values represent averages of 16 analysis, while figures in parentheses represent the standard deviation.

Table 3. Comparison of cumulative metal leaching per surface area from previous studies on CCA- and copper-based preservatives.

Cumulative losses (µg/cm ²)			Exposure conditions	Preservative	Reference
<i>Cu</i>	<i>Cr</i>	<i>As</i>			
10.2	5.0	41.4	Simulated rainfall	CCA	Current Study
39.2	19.1	44.4	Outdoors	CCA	[5]
10.0	15.0	60.0	Outdoors	CCA	[29]
26.9	16.4	52.5	Simulated rainfall	CCA	[2]
18.2	8.0	28.7	Simulated rainfall	CCA	[8]
20.7	7.0	75.0	Outdoors	CCA	[41]
40.0	10.5	180.0	Outdoors	CCA	[1]
22.6	19.9	NR	Outdoors	CCB	[3]
316.0	NR	NR	Outdoors	ACQ	[27]
390.0	NR	NR	Outdoors	ACQ	[40]
290.0	NR	NR	Outdoors	MCQ	[42]
0.9 ^a	NR	NR	Spray	CCA/ACQ/MCQ	[7]
10.0 ^a	NR	NR	Outdoors	CCA/ACQ/MCQ	[7]
25.9 ^a	NR	NR	Immersion	CCA/ACQ/Tanalith E	[6]

^a Values reported in this table are for leached CCA. NR = not reported
CCB = chromated copper borate. ACQ = alkaline copper quaternary. MCQ = micronized copper quaternary.

3.2 CHECK DEVELOPMENT AND CHEMICAL MOBILITY

Check formation was first observed after approximately six wet/dry cycles, with checks reaching widths of up to 0.9 mm and depths of 10 mm. However, substantial variation was noted among samples, with most checks extending across the full length of the specimens. One key limitation of this study was the small dimensions and reduced thickness of the test specimens, which may not fully represent real-world timber performance. The 13 mm board thickness was selected based on prior studies; however, structural timber and decking materials are

typically thicker and larger, influencing moisture movement and crack development. Thicker boards exhibit slower drying rates, more gradual moisture gradients, and reduced susceptibility to moisture-driven crack formation. The smaller specimens used in this study were more susceptible to rapid wetting and drying cycles, likely exaggerating both check formation and preservative migration compared to what would be expected in full-sized construction-grade timber. This suggests that future research should incorporate larger-scale testing to more accurately assess check development and preservative behaviour in field

conditions. Reduced specimen dimensions may have also influenced preservative leaching behaviour.

Thinner boards, with their higher surface-area-to-volume ratio, are more susceptible to rapid moisture ingress and evaporation, which can accelerate preservative migration. In contrast, larger boards have longer preservative diffusion pathways and tend to exhibit higher retention rates due to their greater internal wood volume. As a result, the findings on leaching and preservative mobility from this study may not be directly applicable to full-sized timber used in outdoor structures, where preservative loss and redistribution dynamics are likely to differ significantly. Further research involving larger-scale specimens is necessary to evaluate how preservative movement and retention behave in real-world conditions.

Furthermore, board thickness plays a critical role in determining preservative penetration. The challenges associated with achieving sufficient CCA penetration in *E. nitens* heartwood are well documented [17, 43]. Thinner boards may develop shallower preservative envelopes, making them more susceptible to leaching. In contrast, properly treated thicker boards provide extended diffusion pathways, which can improve long-term preservative retention but may also limit redistribution into checks.

The wafer data indicated that As was the most mobile element, decreasing from 1570.1 ppm (3.68 mg) to 1211.3 ppm (2.84 mg), representing a 23% reduction (Table 1.). As high leachability is well-documented [44–46], and this substantial decrease confirmed its limited fixation stability in hardwoods like *E. nitens*. Despite this measurable loss from the wafers, As levels on the check surfaces remained nearly unchanged—rising by only 0.001 mg—suggesting that it was not redistributed, but instead lost via runoff, which poses implications for both durability and environmental contamination.

In contrast, Cu showed a moderate loss of approximately 10.3%, dropping from 1017.2 ppm (2.39 mg) to 912.7 ppm (2.14 mg) in the wafers. Importantly, Cu concentrations in the check surfaces more than doubled, increasing from 47.1 ppm (0.047 mg) to 107.4 ppm (0.106 mg). This indicated clear evidence of Cu migration from the treated wafer into the adjacent untreated wood, likely facilitated by moisture-driven diffusion. While this supports the concept of "barrier mobility", where mobile Cu may offer surface-level protection in checked areas, it is important to note that the observed Cu concentration in check surfaces (107 ppm) remains well below the 290 ppm threshold identified by Choi et al. (2004) as necessary to inhibit fungal colonisation from spores [1]. This suggests that although redistribution occurred, the concentrations achieved were unlikely to confer meaningful biological resistance under field conditions.

Furthermore, it is worth noting that the wafers used in this study were treated to a much higher retention level than industrially required, deliberately exceeding the H3 standard to ensure detectable migration effects. Despite this, the amount of Cu that migrated into the check surfaces was limited, raising concerns about the practical benefit of Cu redistribution at industrial treatment levels.

The resulting surface accumulation in typical commercial retentions would likely be even less effective, diminishing any potential barrier effect in Australian hardwoods.

Cr data showed a slight decrease, from 3024.6 ppm (7.10 mg) to 3018.3 ppm (7.08 mg), representing a loss of ~0.2%. Although still minimal, this change suggested that a very small fraction of Cr may be susceptible to leaching under repeated wet/dry exposure in hardwoods like *E. nitens*. Cr levels on the check surfaces also increased only marginally, from 21.1 ppm (0.021 mg) to 26.3 ppm (0.026 mg), reinforcing limited Cr migration under moisture cycling.

Combined results showed that while Cu exhibited moderate mobility and may redistribute into exposed checks, Cr remained immobile, and As was highly mobile but poorly retained within the wood system. This differentiation in behaviour has important implications for the long-term performance of CCA-treated hardwoods. In particular, the loss of As without redistribution suggests a potential weakness in insect resistance over time, while Cu mobility, even if present, may be insufficient to offer reliable surface protection; compared to previous outdoor studies conducted on softwoods, where Cu concentrations in surface checks ranged from 180 ppm after five months to 990 ppm after one year [1, 21, 40, 42, 47].

The complex and heterogeneous arrangement of hardwood vessels, fibres, tracheids, rays, and parenchyma presents significant challenges for preservative fixation and leaching, due to anatomical and chemical variability—even within the same species [48]. Furthermore, the presence of extractives and gum veins can cause localised anomalies in CCA penetration and distribution [10]. Hardwoods typically contain higher concentrations of natural extractives, which can chemically interact with preservative components, thereby inhibiting CCA migration and fixation, particularly within or around surface checks [11, 37].

While this study offers important insights into the migration of CCA components in refractory hardwoods, several limitations related to the experimental design should be acknowledged, particularly regarding how they may have influenced preservative movement. A key constraint was the inability to achieve the standard 5 mm penetration depth, primarily due to the low permeability of *E. nitens* heartwood. Unlike more treatable softwoods, which permit deeper and more uniform penetration of waterborne preservatives, *E. nitens* is known for its highly refractory nature, making it difficult to establish a consistent and continuous preservative envelope. To overcome this challenge, a modified approach was used in which wafers were pressure-treated separately and subsequently adhered to the surface of untreated boards, thereby simulating a treated outer shell over an untreated core. While this method enabled the assessment of preservative migration under controlled conditions, it did not fully replicate the behaviour of commercially treated hardwoods where penetration gradients and in-situ fixation chemistry may differ substantially.

Nonetheless, this method introduced potential limitations in preservative migration dynamics. Preservative

penetration in conventional vacuum pressure impregnation (VPI) treatments, relies on cellular uptake mechanisms, which are influenced by factors such as wood chemistry, density, and grain orientation. In contrast, the wafers used in this study were treated separately prior to attachment, meaning that CCA fixation had already occurred before exposure, potentially altering the availability and mobility of metal ions. Under standard treatment conditions, metal ions interact dynamically with wood fibres, undergoing gradual redistribution as they bind to reactive sites within the wood structure. However, in this experimental configuration, where the preservative was already fixed prior to exposure, such natural diffusion pathways may have been restricted. This likely limited the extent of metal migration that would otherwise be expected in samples treated as a single, continuous unit, and should be considered when interpreting the preservative redistribution observed in this study.

The use of epoxy adhesive to attach the treated wafers presented an additional potential limitation. Although care was taken to apply the adhesive only along the wafer edges, its presence may have influenced preservative migration behaviour in several ways. Epoxy is inherently impermeable to both water and chemical diffusion, and as such, it may have partially restricted the lateral movement of CCA components into the check region. Moisture induced capillary action in conventionally VPI-treated timber can facilitate preservative redistribution, particularly during wet/dry cycling. However, the epoxy may have impeded moisture transport, thereby altering the migration pathways of Cu, Cr, and As from the wafers into adjacent untreated wood. Moreover, certain epoxy formulations contain amine-based hardeners or other reactive compounds, which could potentially interact with CCA components, particularly Cr and Cu, affecting their solubility, mobility, or fixation behaviour. These factors should be considered when interpreting the migration patterns observed in this study, as they may not fully reflect the dynamics present in commercially treated, adhesive-free systems.

Although the accelerated weathering cycles employed in this study successfully simulated moisture fluctuations, they did not incorporate several critical factors that influence timber performance under real-world conditions. Notably, ultraviolet (UV) exposure—which is known to degrade lignin—can significantly alter preservative mobility and fixation, potentially enhancing the redistribution of CCA components over time [49]. Additionally, temperature variations, which affect moisture dynamics, check formation, and metal migration, were not replicated in this controlled environment. Fluctuations in temperature can drive thermal expansion, drying gradients, and influence capillary transport, all of which play a role in preservative movement and wood stability in outdoor applications. In addition, the study did not assess the interactions between partially migrated CCA components and biological agents, such as fungi, bacteria, or insects.

Given these limitations, future research should explore direct, full-depth treatment approaches that more accurately represent industrial practice. Techniques such

as incising, pressure-diffusion treatments, or pre-treatment modifications could be employed to enhance preservative penetration and establish a more realistic and continuous preservative envelope in refractory hardwoods like *E. nitens*. Additionally, investigating whether mechanical fixation of wafers—rather than adhesive bonding—could be used may help to minimise the barrier effects introduced by epoxy, which may restrict moisture and chemical movement. Since adhesives are commonly used in engineered wood products, comparative testing of different bonding methods or adhesive formulations would also be beneficial in understanding how they may influence preservative mobility and fixation behaviour. Field-based validation studies that expose samples to natural weathering conditions, including UV radiation, temperature fluctuations, and biological agents would offer a more comprehensive understanding of preservative redistribution, leaching, and long-term performance. These studies would help bridge the gap between controlled laboratory testing and the complex environmental interactions that affect treated timber in service.

While the wafer-based setup enabled a controlled investigation into preservative migration, it does not fully reflect how CCA components behave in conventionally VPI refractory hardwoods. The use of epoxy adhesive, although applied carefully, may have influenced metal transport, and the absence of a fully impregnated preservative envelope limited the extent to which the results can be generalised to real-world treated timber structures. These methodological constraints underscore the importance of developing improved treatment strategies that achieve deeper and more uniform penetration in refractory hardwoods. They also point to the need for further research into the long-term behaviour of preservative redistribution, particularly in the context of engineered wood products, where adhesive bonding and dimensional constraints may significantly alter preservative effectiveness and durability performance in service environments.

4 – CONCLUSION

This study examined the redistribution and leaching behaviour of CCA components in *E. nitens* heartwood under repeated wet/dry cycles simulating accelerated weathering. While Cu exhibited moderate mobility and some degree of surface redistribution into untreated check areas, As was highly leachable and poorly retained, and Cr remained largely immobile. The preferential loss of As without detectable redistribution into checks raises concerns about the long-term resistance of *E. nitens* to insect attack. Meanwhile, Cu levels in the check surfaces increased but remained below the antifungal threshold reported in previous softwood studies, suggesting limited protective benefit.

Despite using an elevated preservative retention, Cu migration into surface checks remained low. This indicates that, under typical industrial treatment concentrations, such redistribution may be insufficient to meaningfully contribute to durability. Cr, as expected, functioned effectively as a fixative, with negligible losses

or movement, confirming its role in preserving overall CCA retention. The small sample size, thin specimens, and use of a pre-treated wafer system adhered with epoxy introduced several limitations. These included restricted preservative migration pathways, limited internal penetration, and reduced comparability with standard VPI-treated products. Additionally, the absence of UV radiation, temperature variability, and biological exposure limits the environmental realism of the weathering simulation.

Ultimately, the study highlights the limited potential of CCA redistribution for secondary protection in refractory hardwoods like *E. nitens*. It reinforces the need for alternative strategies to improve preservative uptake and distribution, such as incising, pressure-diffusion treatments, or chemical modifications. Future research should also explore real-world field exposure, larger specimen dimensions, and interactions with biological agents to validate laboratory findings and inform treatment recommendations for engineered hardwood products.

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