

Support Information

Sustainable production of densified wood as advanced structural materials through oxygen delignification

Naycari Forfora^{1†}, Xiaoxue Zhang^{2,3†}, Carl J. Houtman^{2*}, Roland Gleisner², Peter Kitin², Sara J. Fishwild², Marshall Begel², Xuejun Pan³, Hoon Kim², Ronalds Gonzales^{1*}, J.Y. Zhu^{2,3*}

¹ Dept. of Forest Biomaterials, North Carolina State University, NC 27606, USA

² USDA Forest Products Lab, Madison, WI 53726, USA

³ Dept. of Biological Systems Eng., University of Wisconsin, Madison, WI 53705, USA

Tables S1- S11; Figs. S1-S3

† These two authors equally contributed to the work.

* Corresponding author: junyong.zhu@usda.gov

Table S1 Experimental conditions for basswood board alkaline soaking and oxygen delignification (O₂-delig)

Board labelling	Run abbreviation	NaOH soaking			Actual NaOH loading (g/kg)	O ₂ -delig T (°C)	O ₂ P (psi)	O ₂ -delig time (h)
		NaOH (g/L)	T (°C)	time				
A	hA30T110O90	30	70	2 h	55.26	110	90	1
B	hA30T110O110	30	70	2 h	58.70	110	110	1
C	hA30T90O90	30	70	2 h	53.37	90	90	1
D	wA30T110O90	30	25	7 d	61.34	110	90	1
E	wA30T110O110	30	25	7 d	58.80	110	110	1
F	wA30T90O90	30	25	7 d	55.00	90	90	1
G	wA30T125O110-t05	30	25	7 d	52.96	125	110	0.5
H	wA30T125O110	30	25	7 d	58.49	125	110	1
I	wA50T110O110	50	25	7 d	98.48	110	110	1
J	wA15T110O110	15	25	7 d	27.99	110	110	1
K	Control	N/A	N/A	N/A	55.26	N/A	N/A	N/A

Table S2 List of basswood board weight (g) before and after soaking, and after O₂-delig

Wood board	Initial weight	After NaOH soaking (g)	After O ₂ -delig (g)	Post air-dry (g)	Post air-dry moisture (%)	O ₂ -delig wood yield (%)	Length (cm)	Width (cm)	Thickness (cm)	samples cutout	Run abbreviation
A	726.0	2063.3	1712.1	660.7	8.38	83.38	45.4	17	2	18	hA30T110O90
B	695.2	2055.4	1736.0	628.1	8.47	82.70	45.4	16.7	2	18	hA30sT110O11 0
C	731.0	2031.5	1877.0	678.4	8.50	84.92	45.2	16.9	2	18	hA30T90O90
D	731.6	2227.4	1984.0	651.5	9.38	80.70	45.7	11.9	1.6	12	wA30T110O90
E	740.6	2192.1	2004.0	668.0	9.40	81.72	45.3	14	1.6	15	wA30T110O110
F	804.4	2279.1	2115.9	741.7	9.80	83.17	45.5	15.4	1.6	15	wA30T90O90
G	798.6	2208.4	1892.4	683.1	9.66	77.28	45.3	12.6	1.8	14	wA30T125O110 -t05
H	749.5	2210.9	1955.0	652.8	9.91	78.47	45.4	11	1.8	12	wA30T125O110
I	798.6	2371.5	2186.0	612.8	9.84	69.18	45.1	10.2	1.2	9	wA50T110O110
J	810.8	2324.0	2035.2	713.1	9.22	79.84	45.2	14	1.8	15	wA15T110O110

Mathematical wood mechanical strength enhancing factor (MEF) by densification

Assuming a wood board/panel has a rectangular cross-sectional area with width b and thickness t , then the tensile stress σ , bending modulus of rupture (MOR), and bending modulus of elasticity (MOE) can be expressed as below

$$\sigma = \frac{F'_{max}}{t \cdot b} \quad (S1)$$

$$MOR = \frac{3 \times F_{max} \times l}{2 \times b \times t^2} \quad (S2)$$

$$MOE = \frac{l^3}{4 \times b \times t^3} K \quad (S3)$$

When the wood cross-sectional area thickness is decreased by Δt by densification, the tensile stress, MOR, and MOE can be recalculated below

$$\sigma_{\Delta t} = \frac{F'_{max}}{(t - \Delta t) \cdot b} \quad (S4)$$

$$MOR_{\Delta t} = \frac{3 \times F_{max} \times l}{2 \times b \times (t - \Delta t)^2} \quad (S5)$$

$$MOE_{\Delta t} = \frac{l^3}{4 \times b \times (t - \Delta t)^3} K \quad (S6)$$

The ‘‘Mathematical enhancing factor’’ (MEF) for each of these strength measures can be expressed as below, with $\delta_t = \frac{\Delta t}{t}$ as relative thickness reduction.

$$MEF_{\sigma} = \frac{\sigma_{\Delta t}}{\sigma} = \frac{t}{t - \Delta t} = \frac{1}{1 - \delta_t} \quad (S7)$$

$$MEF_{MOR} = \frac{MOR_{\Delta t}}{MOR} = \frac{t^2}{t^2 - 2t\Delta t + (\Delta t)^2} = \frac{1}{1 - 2\delta_t + \delta_t^2} \quad (S8)$$

$$MEF_{MOE} = \frac{MOE_{\Delta t}}{MOE} = \frac{t^3}{t^3 - 3t\Delta t(t - \Delta t) - (\Delta t)^3} = \frac{1}{1 - 3\delta_t(1 - \delta_t) - \delta_t^3}$$

(S9)

Table S3 Assumptions common to all treatments

Assumptions	Value	Unit
Basis (wood input dry)	1500	kg/day
Wood moisture	12%	
Wood density (dry)	500	kg/m ³
Wood density (max)	1500	kg/m ³
Wood heat capacity	1.3	kJ/kg
Impregnation time	1	hr
Chemical temperature	55	°C
Liquid to wood	3	kg liq/kg wood
Liquid adsorbed	2	kg liq/kg wood
Wash water	1	kg liq/kg wood
Steam pressure	120	psig
Volumetric change press	65%	

Table S4 Results of the mass balance calculations

	Oxygen	Unit
Yield	82%	
Cook Temperature	110	°C
Cook Time	1	hr
Chemical Loading	1%	
Batches/day	8	
Vessel volume	4.7	m ³
Production	9840	kg/day
Make up water	1187	kg/day
Make up Chemicals	38	kg/day
Steam	3047	kg/day
Oxygen	750	kg/day

Table S5 Life cycle inventory to produce advanced wood materials.

	Unit/kg bleached wood	Densified wood – O ₂ -delig
Water	kg	0.12
NaOH	kg	0.00389
Oxygen	kg	0.0762
Steam	kg	0.31
Wood	kg	1.22
Transportation of chemicals	kg.km	8.01
Organics	kg	0.22
Inorganics	g	3.86

Table S6 End-of-life factors for wood and metal-based building materials using WARM (EPA, 2023).

Product	End-of-life factor (kgCO ₂ /kg), combustion	End-of-life factor (kgCO ₂ /kg), landfilling (landfills without LFG recovery)	End-of-life factor (kgCO ₂ /kg), recycling
Densified wood – O ₂ -delig	-0.58	-0.92	-
Steel – HRC	-	-	-1.83
Steel – LRC	-	-	-1.83
Al-alloy – HRC	-	-	-7.2
Al-alloy – LRC	-	-	-7.2

Table S7 ANOVA of wood density and mechanical properties among undensified, densified but differently delignified wood groups

Board labelling	Group label	Density (g/cm ³)	Hardness (MPa)	MOR (MPa)	MOE (GPa) (Short span)
Undensified: pristine wood	<i>X1</i>	0.446±0.039	13.2±1.1	59.5±7.8	1.74
Densified: pristine wood (K) + delignified wood (short impregnation A-C)	<i>X2</i>	0.779±0.014	24.6±1.8	114.5±9.1	8.6±1.3
Densified: delignified wood (long impregnation D-J)	<i>X3</i>	0.996±0.071	67.8±15.8	108.1±4.5	14.4±2.8
<i>p value: X1-X2</i>		<i>0.00007</i>	<i>0.00129</i>	<i>0.00196</i>	
<i>p value: X1-X3</i>		<i>0.00002</i>	<i>0.00238</i>	<i>0.00012</i>	
<i>p value: X2-X3</i>		<i>0.00022</i>	<i>0.00049</i>	<i>0.00014</i>	<i>0.00369</i>

Table S8 ANOVA of densified wood MOR and hardness between O₂-delig paired runs I, J, and D

<i>p values for paired runs</i>	I - J	I - D	J - D
MOR	<i>0.0126</i>	<i>0.0130</i>	<i>0.9999</i>
Hardness	<i>0.6753</i>	<i>0.5063</i>	<i>0.9089</i>

Table S9a Environmental impact categories to produce building materials based on 1 kg of material.

Indicator	Densified wood – O ₂ -delig	Al-alloy – LRC	Al-alloy – HRC	Steel – LRC	Steel – HRC	Unit per cm ³ /MPa
Acidification	1.44E-03	9.94E-02	4.66E-02	7.88E-03	3.91E-03	kg SO ₂ eq
Carcinogenics	7.94E-08	1.44E-05	5.38E-06	9.09E-06	8.97E-06	CTUh
Ecotoxicity	6.19E+00	4.45E+02	2.37E+02	2.06E+02	1.79E+02	CTUe
Eutrophication	1.17E-02	7.36E-02	3.77E-02	8.48E-03	4.96E-03	kg N eq
Fossil fuel depletion	1.15E+00	1.23E+01	7.44E+00	1.11E+00	6.79E-01	MJ surplus
Global warming	6.09E-01	1.89E+01	9.40E+00	2.31E+00	9.12E-01	kg CO ₂ eq
Non carcinogenics	8.75E-08	6.40E-06	3.30E-06	7.93E-07	6.47E-07	CTUh
Ozone depletion	1.22E-08	2.08E-07	1.12E-07	1.23E-08	7.67E-09	kg CFC ⁻¹¹ eq
Respiratory effects	2.93E-04	2.06E-02	1.11E-02	2.93E-03	1.30E-03	kg PM2.5 eq
Smog	3.07E-02	1.14E+00	5.37E-01	1.16E-01	5.65E-02	kg O ₃ eq

Table S9b Environmental impact categories to produce building materials based on specific strength. The comparison of specific strength was based on modulus of rupture (MOR) for densified-wood and ultimate tensile strength (UTS) for the metal alloys. Specific strengths: Advanced-wood, MOR: 221 MPa cm³/g; Al-alloy, UTS: 168 MPa cm³/g; HSSS (specific strength steel), UTS: 168 MPa cm³/g

(<https://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA2024T4>,

https://static.markforged.com/downloads/markforged_datasheet_17-4_ph_stainless_steel.pdf

<https://specialtysteelsupply.com/wp-content/docs/17-4ph.pdf>)

Indicator	Densified wood – O ₂ -delig	Al-alloy – LRC	Al-alloy – HRC	Steel – LRC	Steel – HRC	Unit per cm ³ /MPa
Acidification	6.48E-09	5.89E-07	2.76E-07	4.69E-08	2.33E-08	kg SO ₂ eq
Carcinogenics	3.58E-13	8.51E-11	3.19E-11	5.41E-11	5.34E-11	CTUh
Ecotoxicity	2.79E-05	2.64E-03	1.41E-03	1.23E-03	1.06E-03	CTUe
Eutrophication	5.28E-08	4.36E-07	2.24E-07	5.05E-08	2.95E-08	kg N eq
Fossil fuel depletion	5.17E-06	7.30E-05	4.41E-05	6.63E-06	4.04E-06	MJ surplus
Global warming	2.75E-06	1.12E-04	5.57E-05	1.37E-05	5.43E-06	kg CO ₂ eq
Non carcinogenics	3.95E-13	3.79E-11	1.96E-11	4.72E-12	3.85E-12	CTUh
Ozone depletion	5.48E-14	1.23E-12	6.66E-13	7.31E-14	4.57E-14	kg CFC ⁻¹¹ eq
Respiratory effects	1.32E-09	1.22E-07	6.58E-08	1.75E-08	7.74E-09	kg PM _{2.5} eq
Smog	1.38E-07	6.77E-06	3.19E-06	6.93E-07	3.36E-07	kg O ₃ eq

Table S10: Comparison table for densified wood production.

Parameter	O₂-Delignification (This Work)	Peroxide-Based Delignification	Sulfite-Based Delignification	Alkaline Delignification (NaOH / Carbonate / AQ)
Typical chemical charge	28–56 g/kg NaOH	5–30 wt% H ₂ O ₂ (often with acetic acid)	10–20 wt% Na ₂ SO ₃	High alkaline loadings (typically several wt% NaOH solutions, often at elevated liquor-to-wood ratios)
Temperature	90–110 °C	120–150 °C	100–140 °C	150–170 °C
Pressure	0.6–0.8 MPa O ₂	Atmospheric or autoclave	Atmospheric or mild pressure	Atmospheric or mild pressure
Reaction time	1 h	2–12 h	6–12 h	1–3 h
Lignin removal	10–30%	40–80%	40–70%	60–90%
Environmental issues	No sulfur; low chemical load; no chemical recovery needed	High oxidant cost; safety concerns; wastewater treatment	SO ₂ emissions; sulfite recovery required	High-energy chemical recovery (lime kiln, evaporation)
Mechanical performance after densification	MOR > 220 MPa; Brinell > 80 MPa	MOR 200–250 MPa	MOR 200–250 MPa	MOR 200–300 MPa [3,4]
Scalability	High (low-temperature, low-chemical, no recovery system required)	Moderate (chemical cost & safety)	Low (sulfur handling & recovery)	Low–moderate (requires capital intensive kraft-like recovery system)
Key advantages	Low cost, low temperature, scalable, minimal carbohydrate loss	High delignification; good transparency & moldability	Good delignification	Strong densification; well-studied chemistry
Key drawbacks	Partial delignification only	Expensive chemicals; safety	Sulfur emissions; recovery	High capital cost; high energy
References		https://www.nature.com/	https://www.nature.com/	https://www.research-

		articles/nature25476 https://www.semanticscholar.org/paper/Integration-of-peroxide-delignification-and-acid-Kuznetsov-Levdansky/b57957848c4edb5b398a2d389cf6e2ec2b8d4592	articles/nature25476 https://www.semanticscholar.org/paper/MECHANICAL-PROPERTIES-TESTS-OF-DELIGNIFIED-AND-WOOD-Wehsener-Bremer/4721ee2510c3f8ad4c87438daa9c7b5338e7c368 https://www.mdpi.com/1999-4907/15/6/892	collection.ethz.ch/entities/publication/e922a964-6aa8-47b6-b356-5dc1a28bacc9 https://cerne.ufla.br/site/index.php/CERNE/article/view/3521 https://link.springer.com/article/10.1186/s10086-020-1853-x
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Rough estimate of chemical and energy input costs for wood delignification

Because delignification represents one of the major cost drivers in densified wood production, it is useful to compare the chemical intensity of the present O₂-delig process with conventional alkaline delignification using NaOH reported in the densified wood literature. For example, our earlier study produced densified poplar wood using 2 – 6 wt. % NaOH with a liquor-to-wood ratio of approximately 3 achieved effective delignification (Wang et al, J Mat Sci., 55:14664, 2020). These conditions correspond to gross alkali charges of approximately 0.06–0.18 kg NaOH per kg dry wood prior to densification. After accounting for the reported solids yields of 74–90%, the effective NaOH consumption corresponds to approximately 0.066–0.242 kg NaOH per kg densified wood product. In contrast, the O₂-delig process developed in this study requires approximately 0.0039 kg NaOH and 0.076 kg O₂/kg densified wood according to the life-cycle inventory used for the LCA analysis (Table S5).

A simple screening-level comparison of variable chemical cost can therefore be performed using representative bulk chemical prices (NaOH ≈ \$0.38/kg and industrial oxygen ≈ \$0.25/kg densified wood) (<https://www.chemanalyst.com/Pricing-data/caustic-soda-3>, <https://www.imarcgroup.com/bulk-oxygen-pricing-report>). Under these assumptions, the chemical cost associated with the O₂-delig is approximately \$0.020/kg densified wood (NaOH + O₂). By comparison, the NaOH delignification (Wang et al., J Mat Sci., 55:14664, 2020) ranges from \$0.026-0.092/kg densified wood from NaOH consumption alone.

A simple sensible-heat estimate using the same liquor-to-wood ratio of 3:1 for both delignification processes indicates that heating from 55 °C to the reaction temperature requires approximately 0.59–0.93 MJ/kg densified wood for O₂-delig (90–110 °C), compared with 1.46–2.14 MJ/kg densified wood for a representative NaOH delignification operated at 150–170 °C. Considering natural gas prices (\$0.22/m³) (<https://www.eia.gov/dnav/ng/hist/n3035us3m.htm>), costs associated with sensible heat ranges from \$0.0044-0.0069/kg densified wood for the O₂-delig and \$0.011-0.016/kg densified wood for the NaOH process (<https://link.springer.com/article/10.1007/s10853-020-05034-2>). This corresponds to roughly a 2.1–2.7-fold reduction in thermal energy costs, and a up to a total 4.4-fold time cost reduction (chemical + heat), highlighting the potential economic benefit for O₂-delig. Although this simplified comparison does not include capital investment, heat losses, chemical recovery, or labor

costs, it illustrates that the substantially lower alkali consumption and lower thermal demand of the O₂-delig process can offset the additional oxygen input. A rigorous techno-economic analysis is beyond the scope of this work; however, this preliminary comparison indicates that the O₂-delig can be competitive with conventional alkaline delignification in terms of variable operating cost.

Table S11 Cradle-to-grave carbon footprint results for building materials based on specific strength. The comparison of specific strength was based on modulus of rupture (MOR) for densified-wood and ultimate tensile strength (UTS) for the metal alloys. Specific strengths: Advanced-wood, MOR: 221 MPa cm³/g; Al-alloy, UTS: 168 MPa cm³/g; HSSS (specific strength steel), UTS: 168 MPa cm³/g

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Product	End-of-life factor (kgCO ₂ eq/cm ³ /MPa), combustion	End-of-life factor (kgCO ₂ eq/cm ³ /MPa), landfilling (landfills without LFG recovery)	End-of-life factor (kgCO ₂ eq/cm ³ /MPa), recycling
Densified wood - O ₂ -delig	8.76E-07	-2.20E-07	-
Steel – HRC	-	-	-2.89E-06
Steel – LRC	-	-	5.43E-06
Al-alloy – HRC	-	-	1.78E-05
Al-alloy – LRC	-	-	7.40E-05


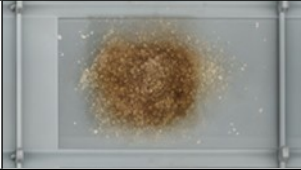
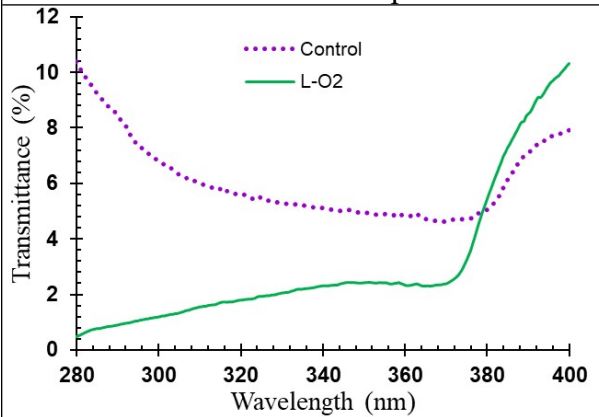
Physical Properties																									
Organic Solvent Dissolution Efficiency (%)																									
Hexane	3																								
Ethanol	8																								
Dioxane	12																								
Aceton	13																								
Acetic acid	26																								
Molecular Weight																									
Mn	1956																								
Mw	3215																								
PDI	1.64																								
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a	6.4																								
b	13.3																								
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Sun Protection SPF																									
Commercial sunscreen (control)	13.9																								
Supplemented 5wt% L-O2	84.6																								
UV Transmittance spectra																									
 <p>The graph displays UV Transmittance spectra. The y-axis is Transmittance (%) from 0 to 12, and the x-axis is Wavelength (nm) from 280 to 400. Two curves are shown: Control (purple dotted line) and L-O2 (green solid line). The Control curve starts at ~10% at 280 nm, dips to ~5% at 370 nm, and rises to ~8% at 400 nm. The L-O2 curve starts at ~0.5% at 280 nm, remains low until 370 nm, and then rises to ~10% at 400 nm.</p> <table border="1"> <caption>Approximate data points from the UV Transmittance spectra graph</caption> <thead> <tr> <th>Wavelength (nm)</th> <th>Control Transmittance (%)</th> <th>L-O2 Transmittance (%)</th> </tr> </thead> <tbody> <tr> <td>280</td> <td>10.0</td> <td>0.5</td> </tr> <tr> <td>300</td> <td>7.0</td> <td>1.5</td> </tr> <tr> <td>320</td> <td>6.0</td> <td>2.0</td> </tr> <tr> <td>340</td> <td>5.5</td> <td>2.5</td> </tr> <tr> <td>360</td> <td>5.0</td> <td>2.5</td> </tr> <tr> <td>380</td> <td>5.0</td> <td>3.0</td> </tr> <tr> <td>400</td> <td>8.0</td> <td>10.0</td> </tr> </tbody> </table>		Wavelength (nm)	Control Transmittance (%)	L-O2 Transmittance (%)	280	10.0	0.5	300	7.0	1.5	320	6.0	2.0	340	5.5	2.5	360	5.0	2.5	380	5.0	3.0	400	8.0	10.0
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Fig. S1 Preliminary characterization of the physical properties of the O₂-delig lignin (collected from all the O₂-delig runs with week-long impregnation)

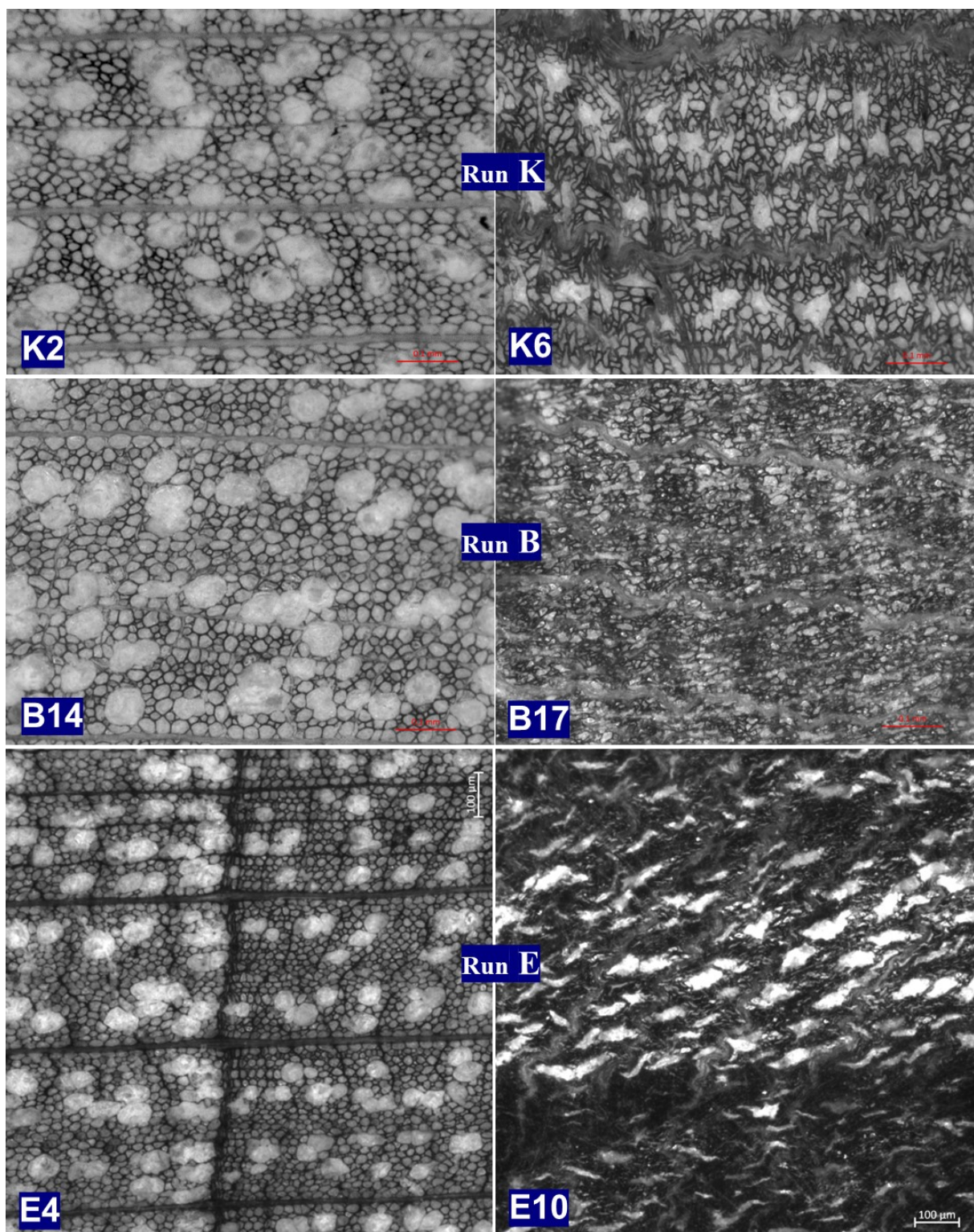


Fig. S2 Effect of wood alkali impregnation for O₂-delign on wood delignification and densification revealed by light microscopy images of anatomical wood cell microstructures. Left column after O₂-delign before densification. Right column after densification. Run K is control without alkali impregnation and O₂-delign. Run B: short (2 h) impregnation time at 70°C; Run E: long (a week) impregnation time at 25°C.

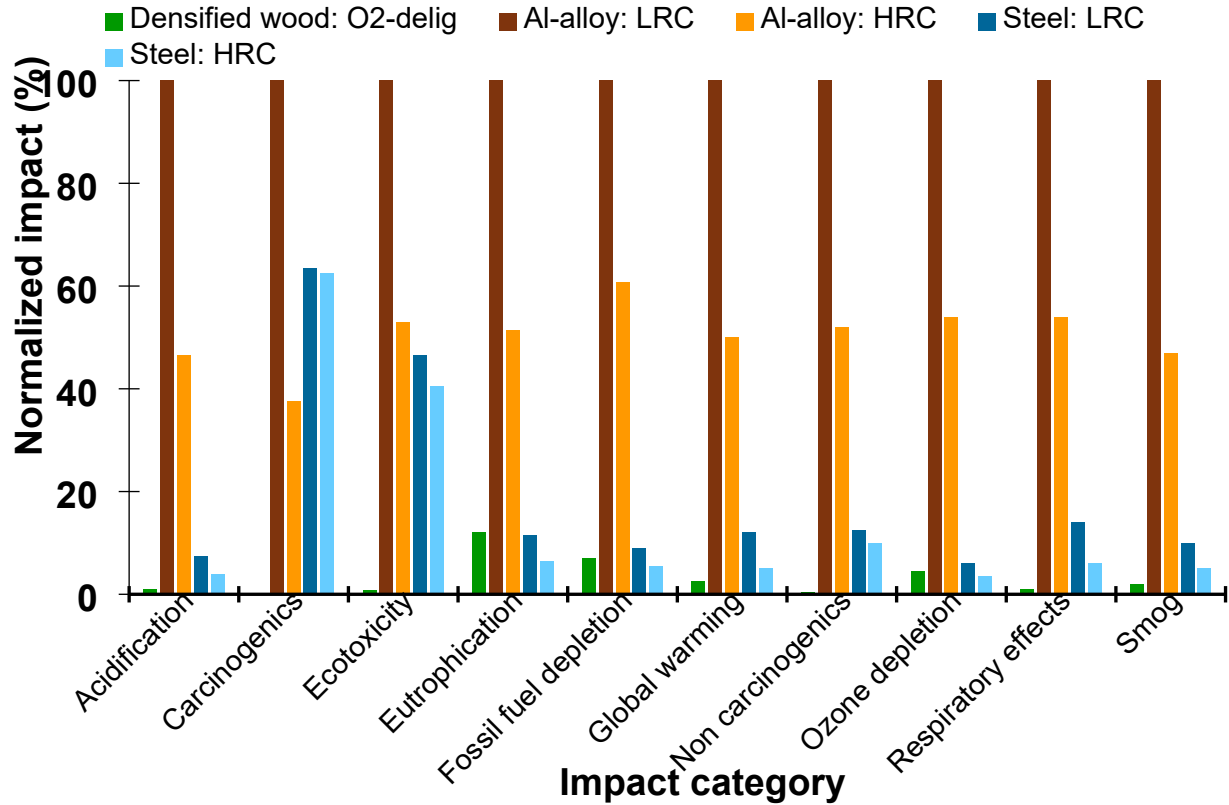


Fig. S3 Cradle-to-gate environmental impacts to produce building materials based on specific strength. Specific strengths: The comparison of specific strengths was based on modulus of rupture (MOR) for densified wood and ultimate tensile strength (UTS) for the metal alloys. Specific strengths: Advanced-wood, MOR: 221 MPa cm³/g; Al-alloy, UTS: 168 MPa cm³/g; HSSS (specific strength steel), UTS: 168 MPa cm³/g

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