Chung Y. Hse*, Todd F. Shupe and Bin Yu

# Rapid microwave-assisted acid extraction of southern pine waste wood to remove metals from chromated copper arsenate (CCA) treatment

**Abstract:** Recovery of metals from chromated copper arsenate (CCA)-treated southern pine wood particles was investigated by extraction in a microwave reactor with binary combinations of acetic acid (AA), oxalic acid (OxA), and phosphoric acid (PhA). Use of OxA was not successful, as insoluble copper oxalate complexes impeded copper removal. The combination of OxA and AA also had adverse effects on copper extraction. In contrast, the combination of AA and PhA enhanced the chromium recovery rate. The highest recovery rate of metals could be achieved with a mixture of 2.75% PhA and 0.5% AA at 130°C for 10 min in the microwave oven. The total recovery rate approached 100% for arsenic, 96.7% for chromium, and 98.6% for copper in a one-step process.

**Keywords:** binary acid solution, CCA-treated wood, microwave extraction

**\*Corresponding author: Chung Y. Hse,** USDA Forest Service, Southern Research Station, Pineville, LA 71360, USA, Phone: +1-318-473-7271, Fax: +1-318-473-7246, e-mail: chse@fs.fed.us
**Todd F. Shupe:** Louisiana Forest Products Development Center, Louisiana State University AgCenter, Baton Rouge, LA 70803, USA
**Bin Yu:** Louisiana Forest Products Development Center, Louisiana State University AgCenter, Baton Rouge, LA 70803, USA

## Introduction

Preservative-treated wood products have a long service life, but sooner or later they fail. It is estimated that approximately $12 \times 10^6$ $m^3$ $year^{-1}$ of spent chromated copper arsenate (CCA)-treated wood products in the United States and Canada will be removed from service in the next 20 years (Kazi and Cooper 2006). Because of their toxic arsenic and chromium contents, which are partly water soluble, their proper disposal is problematic (Townsend et al. 2005; Moghaddam and Mulligan 2008). Landfilling is becoming costly or even impractical

owing to strict regulatory requirements and liability. The literature describes many alternatives of disposal, such as by pulping with organic acids (Stephan et al. 1996), liquefaction and precipitation of the metals (Lin and Hse 2005), hydrothermal treatment (Catallo and Shupe 2008), and pyrolysis (Govaerts et al. 2011; Kemiha et al. 2011), just to mention a few. All these suggested approaches have some disadvantages. The burning of CCA-treated wood is also dubious for reasons of health care and environmental protection. New techniques are needed for recycling and disposal of decommissioned CCA-treated wood.

Exposure of CCA-treated wood to an acid solution leads to the reoxidation of the chromium and to the conversion of the CCA elements into their water-soluble form (Shiau et al. 2000; Clausen 2004; Humer et al. 2004; Gezer et al. 2006; Kazi and Cooper 2006; Kakitani et al. 2007; Janin et al. 2009). In the quoted studies, various organic acids were tested for this purpose, such as oxalic, acetic, citric, and formic acid. These studies indicated that the acid extraction process is slow. However, acid exaction aided by microwave energy accelerates the process (Yu et al. 2009). This study demonstrated that 1) microwave-assisted acid extractions with oxalic acid (OxA), acetic acid (AA), and phosphoric acid (PhA) reduce the reaction times from hours to minutes compared to the conventional methods; 2) OxA extraction effectively removes arsenic (As) and chromium (Cr) but not copper (Cu); 3) AA extraction is highly effective for the removal of As and Cu but not of Cr; and 4) extraction with PhA was less effective than that with either OxA or AA. Extraction with two acids has advantages and can be performed in a one-step process with a combination of two acids or by means of a two-step process consisting of consecutive acid extraction steps.

In the present study, two acids were mixed, and the extraction potential of the binary mixtures of OxA, AA, and PhA was studied. The objective of the present study was to develop a cost-effective, microwave-based, double-acid extraction system to maximize the removal of CCA elements from spent CCA-treated wood. This task was addressed by optimizing acid combinations

and concentrations, extraction times, and the reaction temperature to minimize any environmental impact.

# Materials and methods

CCA-treated southern pine (*Pinus* sp.) guard rail posts were obtained from Arnold Forest Products Co. (Shreveport, LA, USA). The posts were reduced to sawdust on a table saw. The sawdust was screened to collect sawdust that passed through a 40-mesh sieve and retained on a 60-mesh sieve and then dried to a constant weight in an oven maintained at 50°C. The dried sawdust was stored in a heavy-duty zip-lock polyethylene bag and investigated without further treatment. All acids for extraction were of reagent grade and obtained from commercial sources. The acids were diluted with deionized water.

The acid extractions were carried out in a Milestone MEGA 1200 laboratory microwave oven. Unless otherwise stated, 1 g of wood meal was weighted into a 100-ml Teflon reaction vessel with a magnetic stirring bar. The concentration of acids in solutions is given as percent by weight per volume of deionized water (g/v). Twenty milliliters of acid combinations of AA/OxA, AA/PhA, or PhA/OxA was then added to the reaction vessel and thoroughly mixed. The reaction vessel was then placed on the rotor tray inside the microwave cavity. The temperature was monitored by an automatic fiber optic temperature control system. Based on the monitored temperature, the output power was auto-adjusted during acid extraction. In this study, the temperature was increased from room temperature to 160°C at a heating rate of 32.5°C min$^{-1}$ and then was kept constant for 30 min, unless otherwise indicated. After a cooling period of 30 min at the end of acid extraction, the extracted liquids were vacuum filtered through Whatman No. 4 filter paper and then diluted to 100 ml in a volumetric flask for the determination of the CCA elements. The solid wood residue retained on the filter paper was oven dried and then subjected to acid digestion prior to the determination of chromium, arsenic, and copper. Samples were digested in accordance with American Wood Protection Association Standard A7-93 (AWPA 2008). The procedure requires that solid residues be accurately weighed into 100-ml test tubes. For each gram of solid residue, 15 ml of nitric acid was added. A digestion blank along with the samples was also prepared. The test tubes were placed into an aluminum heating block, and the temperature was increased and maintained at 120°C until a transparent liquid was obtained. The transparent liquid was cooled to room temperature and 5 ml of $H_2O_2$ was dropwise added. If the solution was not clear after this treatment, the temperature was increased and another 5 ml of hydrogen peroxide was added. The sample was continually heated until approximately 1 ml of the sample solution remained in the test tube. The sample was carefully transferred into a 25-ml volumetric flask and then diluted with distilled water to a 25-ml solution for the determination of the Cr, As, and Cu in the residue by means of inductive coupled plasma atomic emission spectroscopy (ICP-AES). The recovery rate (RR, %) of the elements in acid extraction was then determined with the following formula: RR (%)=$100 \times Ws/(Ws+Wr)$, where $Ws$ is the weight of the CCA elements in the acid-extracted solution and $Wr$ is the weight of the CCA elements in the wood residue.

Data were evaluated by analysis of variance (ANOVA) with SAS 9.0 software (SAS 2008). The significant differences between mean values were determined by Duncan's multiple range test.

# Results and discussion

## Experiments with OxA/AA mixtures

CCA recovery rate ($RR_{CCA}$) with binary acid solutions consisting of oxalic (OxA) and acetic acid (AA) are summarized in Table 1. In all acid combinations, >98% and 99% of As and Cr could be recovered, respectively. However, the average Cu recovery was surprisingly low (30.1–34.6%) in view of the previous finding that 97.5% Cu removal can be attained with only AA extraction in a microwave reactor (Yu et al. 2009). Probably, insoluble complexes between OxA and copper occurred (Pizzi 1982, 1990; Bull 2001; Humer et al. 2004; Kakitani et al. 2009). Kirsch and Maurer (1998) reported on the formation of mixed acid complexes containing AA and OxA in the organic phase. In addition, in the presence of anhydrous AA at high temperatures, OxA can decompose quickly (Pszonicki and Tkacz 1976). This is the reason why mixtures of AA/OxA are not suitable for CCA extraction.

## Experiments with PhA/OxA or PhA/AA

Table 2 summarizes the average RR of CCA elements with combinations of PhA with either OxA or AA. In the mixed PhA and OxA solution, the RR of Cr and As approached 100%. However, the highest $RR_{Cu}$ was 52%. For comparison, in a one-step OxA extraction (microwave reactor) the yield was 39% and in a PhA extraction it was 79% (Yu et al. 2009). Accordingly, the efficiency of PhA in the binary solution is not satisfactory for copper recovery. In a two-step process beginning with 1 h of OxA extraction followed by a 3-h PhA extraction, Kakitani et al. (2006) found that the two acids alone were ineffective for remediation of CCA-treated wood.

| Concentration of acids | | Recovery rate of elements | | |
|---|---|---|---|---|
| AA (%) | OxA (%) | As (%)[a] | Cr (%)[a] | Cu (%)[a] |
| 1.5 | 1 | 99.65±0.24 | 99.88±0.49 | 34.57±1.02 |
| 1 | 1 | 99.67±0.45 | 99.89±1.03 | 32.93±1.18 |
| 0.5 | 1 | 99.59±0.27 | 99.65±0.96 | 31.50±0.85 |
| 1.5 | 0.5 | 99.56±1.45 | 99.43±1.73 | 31.47±0.91 |
| 1 | 0.5 | 99.21±0.65 | 99.37±0.83 | 30.60±0.79 |
| 0.5 | 0.5 | 98.78±0.79 | 99.38±1.28 | 30.11±1.32 |

**Table 1** Recovery rate of elements by extraction with mixtures of acetic acid (AA) and oxalic acid (OxA) with the concentrations indicated. Conditions: microwave reactor at 160°C for 30 min.
[a]Each value is an average of three sample replications.

| Concentration of acids (%) | | Recovery rate of elements | | |
|---|---|---|---|---|
| PhA (%) | Other acids (%) | As (%)[a] | Cr (%)[a] | Cu (%)[a] |
| 0.5 | OxA 1 | 99.52±0.23 | 97.12±0.21 | 33.82±1.15 |
| 1.25 | OxA 1 | 99.12±0.13 | 97.39±0.49 | 36.49±1.05 |
| 2.0 | OxA 1 | 98.90±0.55 | 97.67±0.49 | 41.30±2.01 |
| 3.5 | OxA 1 | 99.58±1.05 | 98.77±1.03 | 52.14±1.49 |
| 0.5 | AA 1 | 94.05±2.28 | 23.52±1.72 | 95.38±2.42 |
| 1.25 | AA 1 | 96.66±1.38 | 50.03±2.09 | 97.38±1.02 |
| 2.0 | AA 1 | 99.01±0.60 | 72.18±1.45 | 97.46±0.67 |
| 3.5 | AA 1 | 99.52±0.91 | 98.10±1.37 | 98.60±0.93 |

**Table 2** Recovery rate of elements by extraction with mixtures of phosphoric acid (PhA), oxalic acid (OxA), and acetic acid (AA) with the concentrations indicated. Conditions: microwave reactor at 160°C for 30 min.
[a]Each value is an average value of three sample replications.

As demonstrated above, combinations of PhA and AA are effective for removal of As and Cu, but the challenge is the chromium recovery. In this context, it is remarkable that the addition of 1.0% AA into a series of PhA solutions enhanced the $RR_{Cr}$ in linear proportion to the PhA concentration, whereas the PhA concentration of 3.5% was most effective with a $RR_{Cr}$ of 98.1% (Tables 2 and 3).

| Concentration of acids | | Recovery rate of elements | | |
|---|---|---|---|---|
| PhA (%) | AA (%) | As (%)[a] | Cr (%)[a] | Cu (%)[a] |
| 3.50 | 2 | 99.52 | 99.30 | 99.02 |
| 2.75 | 2 | 99.48 | 99.21 | 99.01 |
| 2.00 | 2 | 98.89 | 74.32 | 98.23 |
| 1.25 | 2 | 96.77 | 51.77 | 97.99 |
| 0.50 | 2 | 95.50 | 25.79 | 96.87 |
| 3.50 | 1.5 | 99.52 | 99.21 | 98.97 |
| 2.75 | 1.5 | 99.24 | 97.98 | 98.65 |
| 2.00 | 1.5 | 98.66 | 73.33 | 97.98 |
| 1.25 | 1.5 | 97.79 | 49.36 | 97.56 |
| 0.50 | 1.5 | 95.01 | 24.57 | 96.22 |
| 3.50 | 1 | 99.52 | 98.10 | 98.60 |
| 2.75 | 1 | 99.06 | 96.37 | 98.56 |
| 2.00 | 1 | 99.01 | 72.18 | 97.46 |
| 1.25 | 1 | 96.66 | 50.03 | 97.38 |
| 0.50 | 1 | 94.05 | 23.52 | 95.38 |
| 3.50 | 0.5 | 99.61 | 95.35 | 98.01 |
| 2.75 | 0.5 | 99.01 | 96.23 | 98.07 |
| 2.00 | 0.5 | 98.54 | 70.37 | 97.36 |
| 1.25 | 0.5 | 96.03 | 48.95 | 96.85 |
| 0.50 | 0.5 | 93.57 | 23.06 | 95.12 |

**Table 3** Recovery rate of elements by extraction with mixtures of PhA and AA with the concentrations indicated. Conditions: microwave reactor at 160°C for 30 min.
[a]Each value is an average value of three sample replications.

## Experiments with PhA/AA systems

Table 3 summarizes the RR of CCA metals obtained by the combination of five PhA and four AA concentrations in microwave extraction at 160°C for 30 min. ANOVA indicates that PhA concentration has a significant effect on the $RR_{CCA}$, but the effect of the AA concentration is not significant within the concentration range evaluated. The results of the Duncan's multiple range tests for significant means are summarized in Table 4. The average RRs were 99.3% (As), 97.5% (Cr), and 98.4% (Cu), when the concentration of PhA was 2.75% regardless of the concentration of AA. Obviously, the average $RR_{Cr}$ cannot be improved significantly by raising the PhA concentration above 2.75%; however, the $RR_{Cr}$ decreased significantly with PhA concentration decrements below 2.75%. Therefore, a PhA concentration of 2.75% was chosen for additional process optimization experiments.

Although the effect of AA concentration was statistically not significant, a RR above 99% was attained for all CCA elements when AA concentration increased to 2.0%. The concentration of PhA is more important as stated above in terms of $RR_{Cr}$ (Table 4). Chromium has the highest resistance to extraction because of its strong bonding capacity with lignin (Pizzi 1990). However, it is not fully clear how the presence of AA in PhA improves the chromium recovery, and the following literature overview may help with speculation about the reasons.

For the preparation of activated carbon (Jagtoyen and Derbyshire 1998; Zuo et al. 2009) and flame-retardant

| Concentration of acids | n[a] | Recovery rate of elements | | |
|---|---|---|---|---|
| | | As (%) mean[b] | Cr (%) mean[b] | Cu (%) mean[b] |
| PhA (%) | | | | |
| 0.50 | 12 | 94.53 D | 23.78 D | 95.90 D |
| 1.25 | 12 | 96.82 C | 50.03 C | 97.22 C |
| 2.00 | 12 | 98.78 B | 73.55 B | 97.80 B |
| 2.75 | 12 | 99.26 A B | 97.47 A | 98.44 A |
| 3.5 | 12 | 99.52 A | 97.99 A | 98.71 A |
| AA (%) | | | | |
| 0.50 | 15 | 97.42 A | 66.67 A | 97.29 A |
| 1.00 | 15 | 97.66 A | 68.5 A | 97.47 A |
| 1.50 | 15 | 98.01 A | 68.67 A | 97.62 A |
| 2.0 | 15 | 98.03 A | 70.08 A | 98.06 A |

**Table 4** Summary of the Duncan's multiple range tests for significant means on the effect of concentrations of PhA and AA on the CCA recovery rate.
[a]n indicates number of samples.
[b]Different letters indicate significantly different.

products (Inagaki et al. 1976) from various lignocellulosic materials, PhA was already successfully applied. PhA-treated lignocellulosic materials begin to lose carbonyl and methyl groups in hemicelluloses at 50°C; lignin starts to change at 100°C, and substantial oxidation of cellulose occurs and ketones are formed at 150°C (Jagtoyen and Derbyshire 1998). Polymer chains are split around 150°C (Solum et al. 1995). The treatment of cellulose with PhA resulted in reduced substrate crystallinity and increased accessibility (Saito et al. 1994; Nilsson et al. 1995). Interestingly, Dobele et al. (1999) found that PhA pretreatment of cellulose enhances essentially the yield of levoglucosenone in a subsequent pyrolysis step, probably by promoting the dehydration of the anhydroglucose units. Thus, it is possible that these characteristic reactions of PhA may each contribute to chromium recovery. For instance, the composition and structural changes in lignin induced by PhA treatment may weaken the bond binding the metal-lignin complexes to increase the chromium removal. Furthermore, decreased crystallinity and cellulose surface exposure by solubilization of hemicelluloses by the PhA treatment may result in increasing access of AA to enhance the metal recovery rate.

## Optimization of the microwave reactor system

The $RR_{CCA}$ for different reaction times and temperatures is summarized in Table 5. All extractions were carried out at fixed acid concentrations of 2.75% (PhA) and 0.5% (AA). ANOVA indicates that reaction temperature has a significant effect on the $RR_{CCA}$, whereas reaction time is not relevant in this regard. The results of the Duncan's multiple range tests for significant means are summarized in Table 6. Average maximum RR was attained for As and Cu at 100°C; but, as expected, Cr required 130°C to reach the maximum RR. The $RR_{Cr}$ was consistently lower than that of As and Cu even at higher temperatures. The effects of PhA concentration (Table 4) and those of temperature (Table 6) show the importance of process optimization. A concentration of 0.5% AA and 2.75% PhA and an extraction time of 10 min at 130°C were the best optimum for chromium dissolution. In a microwave reactor, the extraction is more rapid than that obtainable with conventional heating.

For comparison, Kazi and Copper (1998) found in a sequential extraction with formic acid and OxA (2 h, 50°C, 10% acid concentration) that 95% Cr, 100% Cu, and 88% As can be removed. Kakitani et al. (2006) found in a

two-step extraction process at 75°C with citric acid (1 h, 6.4%) followed by PhA (3 h, 3.26%) that 100% As, 99.1% Cu, and 95.7% Cr can be eliminated from treated wood.

The found optimum in the present study (0.5% AA and 2.75% PhA in microwave extraction) is substantially more convenient than the acid extraction with 10% acid concentration (Kazi and Copper 1998) and the two-step method of 6.4% citric acid and 3.26% PhA extraction (Kakitani et al. 2006) with conventional heating.

| Temperature (°C) | Time (min) | **Recovery rate of elements** | | |
|---|---|---|---|---|
| | | As (%) | Cr (%) | Cu (%) |
| 60 | 10.00 | 67.84 | 33.06 | 81.89 |
| 60 | 20.00 | 77.34 | 40.98 | 91.34 |
| 60 | 30.00 | 83.80 | 51.12 | 92.94 |
| 70 | 10.00 | 84.05 | 47.35 | 91.61 |
| 70 | 20.00 | 91.02 | 60.92 | 94.61 |
| 70 | 30.00 | 93.40 | 65.21 | 94.98 |
| 80 | 10.00 | 92.82 | 64.99 | 92.41 |
| 80 | 20.00 | 94.20 | 70.76 | 96.37 |
| 80 | 30.00 | 95.55 | 77.23 | 96.94 |
| 100 | 10.00 | 98.16 | 78.76 | 97.27 |
| 100 | 20.00 | 98.83 | 85.14 | 97.35 |
| 100 | 30.00 | 99.10 | 88.26 | 97.90 |
| 130 | 10.00 | 99.57 | 93.39 | 98.50 |
| 130 | 20.00 | 99.60 | 95.20 | 98.63 |
| 130 | 30.00 | 99.80 | 96.70 | 98.70 |
| 160 | 10.00 | 99.56 | 95.78 | 98.50 |
| 160 | 20.00 | 99.62 | 96.20 | 98.70 |
| 160 | 30.00 | 99.81 | 98.10 | 98.75 |

**Table 5** Effects of microwave extraction temperature and time on the recovery rate of elements with fixed concentrations of 0.5% AA and 2.75% PhA.

| | $n$[a] | As (%) mean[b] | Cr (%) mean[b] | Cu (%) mean[b] |
|---|---|---|---|---|
| **Temperature (°C)** | | | | |
| 60 | 9 | 76.33 D | 41.72 E | 88.73 C |
| 70 | 9 | 89.49 C | 57.88 D | 93.71 B |
| 80 | 9 | 94.19 B | 70.99 C | 95.51 B |
| 100 | 9 | 98.70 A | 84.40 B | 97.44 A B |
| 130 | 9 | 99.51 A | 95.10 A | 98.61 A |
| 160 | 9 | 99.66 A | 96.69 A | 98.64 A |
| **Time (min)** | | | | |
| 10 | 18 | 90.33 A | 68.91 A | 93.32 A |
| 20 | 18 | 93.42 A | 74.87 A | 96.30 A |
| 30 | 18 | 95.19 A | 79.60 A | 96.70 A |

**Table 6** Summary of the Duncan's multiple range tests for significant means on the effect of temperature and time on the CCA recovery rate.
[a]$n$ indicates number of samples. [b]Different letters indicate significantly different.

## Conclusions

The results show that diluted PhA mixed with AA is very effective to recover CCA elements in a microwave reactor within a short period. A binary acid solution consisting of 2.75% PhA and 0.5% AA (10-min reaction time at 130°C) is optimal to achieve the maximum recovery rate of all CCA elements. However, larger-sized wood chips should be extracted to simulate the industrial praxis. Further research concerning AA concentration, reaction time and temperature, along with how to best utilize metal-free wood is needed to maximize economic viability.

## References

AWPA. Annual Book of Standards 2008. American Wood Protection Association, Birmingham, AL, 2008.

Bull, D.C. (2001) The chemistry of chromate copper arsenate II. Preservative-wood interactions. Wood Sci. Technol. 34: 459–466.

Catallo, W.J., Shupe, T.F. (2008) Hydrothermal treatment of mixed preservative-treated wood waste. Holzforschung 62: 119–122.

Clausen, C.A. (2004) Improving the two-step remediation process for CCA-treated wood: Part I. Evaluating oxalic acid extraction, Waste Manage. 24:401–405.

Dobele, G., Rossinskaja, G., Telysheva, G., Meier, D., Faix, O. (1999) Cellulose dehydration and depolymerization reactions during pyrolysis in the presence of phosphoric acid. J. Anal. Appl. Pyrolysis 49:307–317.

Gezer, E.D., Yildiz, U., Dizman, E., Temiz, A. (2006) Removal copper, chromium and arsenic from CCA-treated yellow pine by oleic acid. Build. Environ. 41:380–385.

Govaerts, J., Vandersickel, A., Helsen, L. (2011) Simulation of a thermochemical packed bed reactor developed to treat dried chromated copper arsenate (CCA) impregnated wood waste. High Temp. Mater. Processes 27:319–326.

Humer, H., Pohleven, F., Sentjurc, M. (2004) Effect of oxalic acid, acetic acid, and ammonia on leaching of Cr and Cu from preserved wood. Wood Sci. Technol. 37:463–473.

Inagaki, N., Nakamura, S., Asai, H., Katsuura, K. (1976) Phosphorylation of cellulose with phosphoric acid and thermal degradation of the product. J. Appl. Polym. Sci. 20: 2829–2836.

Jagtoyen, M., Derbyshire, F. (1998) Activated carbons from yellow poplar and white oak by $H_3PO_4$ activation. Carbon 36: 1085–1097.

Janin, A., Blais, J.F., Mercier, G., Drogui, P. (2009) Optimization of a chemical leaching process for decontamination of CCA-treated wood. J. Hazard. Mater. 169:136–145.

Kakitani, T., Hata, T., Kajimoto, T., Imamura, Y. (2006) Designing a purification process for chromium-, copper-, and arsenic-contaminated wood. Waste Manage. 26:453–458.

Kakitani, T., Hata, T., Katsumata, N., Kajimoto, T., Koyanaka, H., Imamura, Y. (2007) Chelating extraction for removal of chromium, copper, and arsenic from treated wood with bioxalate. Environ. Eng. Sci. 24:1026–1037.

Kakitani, T., Hata, T., Kajimoto, T., Koyanaka, H., Imamura, Y. (2009) Characteristics of a bioxalate chelating extraction process for removal of chromium, copper and arsenic from treated wood. J. Environ. Manage. 90:1918–1923.

Kazi, F.K.M., Cooper, P.A. Solvent extraction of CCA-C from out-of-service wood. IRG/WP 98-50107. International Research Group on Wood Preservation, Stockholm, Sweden, 1998.

Kazi, F.K.M., Cooper, P.A. (2006) Method to recover and reuse chromated copper arsenate wood preservative from spent treated wood. Waste Manage. 26:182–188.

Kemiha, M., Nzihou, A., Mateos, D. (2011) Agglomeration of metals during pyrolysis of chromated copper arsenate (CCA) treated wood waste. High Temp. Mater. Processes 27:361–368.

Kirsch, T., Maurer, G. (1998) Distribution of binary mixtures of citric, acetic and oxalic acid between water and organic solutions of tri-n-octylamine: Part II. Organic solvent methylisobutylketone. Fluid Phase Equilib. 142:215–230.

Lin, L., Hse, C.-Y. (2005) Liquefaction of CCA-treated wood and elimination of metals from the solvent by precipitation. Holzforschung 59:285–288.

Moghaddam, A.H., Mulligan, C.N. (2008) Leaching of heavy metals from chromated copper arsenate (CCA) treated wood after disposal. Waste Manage. 28:628–637.

Nilsson, U., Barron, N., McHal, L., McHale, A.P. (1995) The effects of phosphoric acid pretreatment on conversion of cellulose to ethanol at 45°C using the thermotolerant yeast *Kluyveromyces marxianus* IMB3. Biotechnol. Lett. 17:985–988.

Pizzi, A. (1982) The chemistry and kinetic behavior of Cu-Cr-As/B wood preservatives: IV. Fixation of CCA to wood. J. Polym. Sci., Part A: Polym. Chem. 20:739–764.

Pizzi, A. (1990) Chromium interactions in CCA/CCB wood preservatives: 2. Interactions with lignin. Holzforschung 44:419–424.

Pszonicki, L., Tkacz, W. (1976) Complexes of morin and quercetin with boric acid and oxalic acid in acetic acid medium. Fluorimetric determination of boron. Anal. Chim. Acta 87:177–184.

Saito, N., Shimizu, Y., Taqkai, M., Hayashi, J. (1994) Super absorbent materials prepared from lignocellulosic materials by phosphorylation: IV. Fine structure and water absorbency. Sen-i Gakkaishi 49:197–201.

SAS. SAS STAT User's Guide. SAS Institute, Cary, NC, 2008.

Shiau, R.J., Smith, R.L., Avellar, B. (2000) Effects of steam explosion processing and organic acids on CCA removal from treated wood waste. Wood Sci. Technol. 34:377–388.

Solum, M.S., Pugmire, R.J., Jagtoyen, M., Derbyshire, F. (1995) Evolution of carbon structure in chemically activated wood. Carbon 33:1247–1254.

Stephan, I., Peek, R.-D., Nimz, H. (1996) Detoxification of salt-impregnated wood by organic acids in a pulping process. Holzforschung 50:183–187.

Townsend, T., Dubey, B., Tolaymat, T., Solo-Gabriele, H. (2005) Preservative leaching from weathered CCA-treated wood. J. Environ. Manage. 75:105–113.

Yu, B., Hse, C.Y., Shupe, T.F. Rapid microwave-assisted acid extraction of metals from chromate copper arsenate (CCA)-treated southern pine wood. IRG/WP 09-50262. International Research Group on Wood Preservation, Stockholm, Sweden, 2009.

Zuo, S.L., Yang, J.X., Liu, J.L., Cai, X. (2009) Significance of the carbonization of volatile pyrolytic products on the properties of activated carbons from phosphoric acid activation of lignocellulosic material, Fuel Process. Technol. 90:994–1001.