The Use of Chemical and Biological Agents in the Recovery of Heavy Metals from Treated Woods – A Brief Review

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This manuscript provides a brief review about chemical and biological agents used to bioremediate treated wood waste. Wood preservatives have been used to increase wood's useful life, because any species is subject to decay. Studies indicate that the disposal of treated wood after its service has drawn concern and scrutiny. Practices have included disposal in landfills or construction sites as well as destruction by burning, so it is apparent that more environmentally friendly options are needed. To mitigate these problems, acidic agents, fungi, and bacteria can be used as alternatives to remove heavy metals. At optimum temperature and concentration, acids play a major role in the removal process. The process is enhanced when a bioremediation technique is used after chemical extraction. In fact, bioremediation has been shown to be a remarkable technique for recovering copper, arsenic, creosote, and other compounds. The major drawback is the extensive duration of fungal activity for release of heavy metals.

Keywords: Treated wood; Chromated copper arsenate; Bioremediation; Waste management

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INTRODUCTION

One of the factors that increases the useful life of forest products in service is preservative treatment. The majority of commercial species are susceptible to deterioration by fungi and/or termites. It is widely known that the most common methods to preserve wood are those that employ waterborne preservatives under pressure and vacuum cycles. Chromated copper arsenate (CCA) is the most widely used wood preservative around the world (Stinson 1992). However, its use in residential construction was voluntarily discontinued in 2003 in the United States. As a result of this decision, CCA-treated wood can no longer be used to construct residential structures such as playground equipment, decks, picnic tables, landscaping features, fences, patios, and walkways. Figure 1 shows the possible production of a waterborne preservative, with disposal of CCA-treated wood and alternative copper treated wood in the U.S.

There has been no discussion regarding the effectiveness of waterborne preservatives against wood decay; however, according to Chen (2015) any treated wood is subjected to the depletion of the wood preservative. After this point, the problems with disposal and reuse of this material begin with potential risks to human health and environment.

Clausen (2004) argued that special attention must be given to wood products treated with CCA, due to disposal of chromium (Cr) and arsenic (As) in landfills. Helsen *et al.* (1998) pointed out that the presence of these chemicals from treated wood may bring risks during the burning process by releasing toxic airborne substances or causing soil and groundwater contamination when incorrect disposal is used.

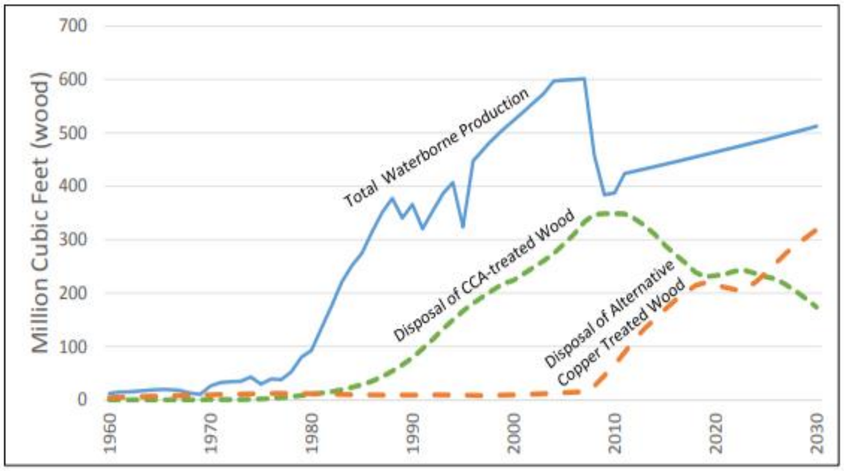

Fig. 1. Projected amounts of CCA and Copper-treated wood in the U.S disposal sector (Solo-Gabriele and Townsend 2017)

Regarding European countries, the wood preserving industry produced around 6.5 million m^3 of pressure-treated wood in 2014. Garden timber was responsible for 44% of the production, followed by construction timber (21%), small roundwood (15%), and sleepers (6%). Figure 2 shows the European industry production categorized by the impregnating type. The most commonly used preservatives are copper compounds, containing ammoniacal copper quaternary or copper azole. Preservatives also contain chromium, boric acid, and/or water-based micro emulsions and include azoles or quaternary ammonium compounds (Salminen *et al.* 2014).

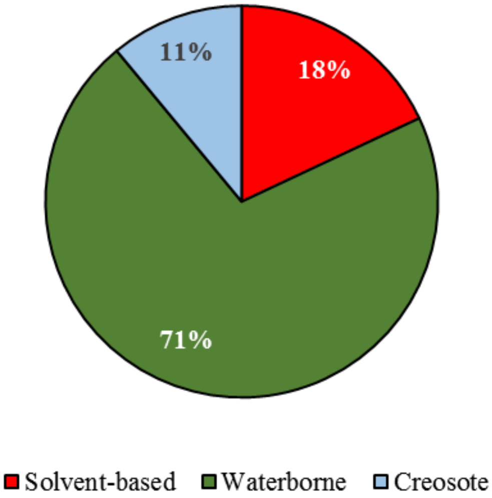

Fig. 2. European wood preserving industry production by impregnating type (Solo-Gabriele and Townsend 2017)

To improve the utilization of the wood and the pieces of treated wood at the end of its useful life, techniques have been developed to remove the chemical compounds used by the preservative treatment, using an environmentally correct manner. Proper disposal promotes the reuse of the residues and treated wood parts (Lin and Hse 2005; Kazi and Cooper 2006; Nanseu-Njiki *et al.* 2007; Pan 2010; Kin *et al.* 2015). The aim of this study was to investigate, through literature review, the principal techniques used to extract heavy metals from treated wood by use of biodegrading organisms or chemicals agents.

Treated Wood Disposal and its Implications

Most of the remediation research has been directed to water and soil remediation, where researchers have focused on arsenic removal. Arsenic has drawn attention worldwide, being used as pesticides, herbicides, wood preservatives, mining, and smelting. However, other metals are also targeted, such as cadmium, nickel, lead, manganese, and copper. To mitigate this issue, phytoremediation with shrubs, grasses, trees, plants, and bark substrates have been done as well as chelating agents, such as EDTA and tannin acid (Randall *et al.* 1974; Gusiatin *et al.* 2014; Cay *et al.*. 2015; Xue *et al.* 2017; Gusiatin *et al.* 2017; Wang *et al.* 2018; Xue *et al.* 2018).

According to Lin and Hse (2005), the disposal of treated wood, mainly CCA, after the end of its useful life has become an important environmental issue. Kartal and Imamura (2003) state that the most common final provisions of this type of material such as burial at construction sites, burning and landfill as solid waste, have become impracticable due to the strict restrictions and environmental concerns.

Federal regulations do not classify chemically treated wood as hazardous waste based on the Resource Conservation and Recovery Act – RCRA (U.S Army Public Health Center 2017). Currently, the Environmental Protection Agency – EPA recommends disposal of chemically treated wood as a nonhazardous solid waste by incineration in a commercial or industrial incinerator or burial in a properly operated, permitted sanitary landfill (Office of the Solid Waste, 2009). However, the EPA recommends that generators contact their State and local authorities, as some states may have more stringent policies or regulations concerning the disposal of treated wood.

The definition of construction and demolition (C&D) wastes varies from state to state, as do landfill disposal regulations. Twenty-three states require C&D landfills to be lined; other states do not (Townsend *et al.* 2004; Clark *et al.* 2006). If leachate from unlined landfills contains elevated levels of As, Cr, and copper (Cu) from CCA-treated wood disposal, it may represent a potential risk to the underlying groundwater.

Townsend *et al.* (2004) encountered wood as residue at construction sites or manufacturing plants as well as sawdust form for determining CCA leaching characteristics with the objective of simulating disposal scenario. Several leaching procedures were carried out according to the sample dimension and purpose (influence of pH and particle size, for instance). These procedures included SW-846 test method 1311, 1312, 1310B, and 1320 from EPA, as well as test methods from the Department of Toxic Substances Control in California.

In the Hazardous Waste Characteristics Document from the EPA (2009), arsenic and chromium had a regulatory level of 5 mg/L of generated liquid waste after filtration. Townsend *et al.* (2004) found for the test method 1311 that 84% of the samples exceeded the As threshold and none of the samples exceeded Cr limits. For the method 1312, 69% of the samples exceeded the As threshold and none the Cr threshold. In May 2009, EPA deployed the national primary drinking water regulation, where the threshold for As is 0.01 mg/L, Cr 0.1 mg/L, and Cu 0.015 mg/L. In that case, the leaching of CCA treated wood is above the drinking water standards, potentially posing a risk to groundwater.

According to the Environment Directorate General of the European commission – European Commission (2018), wastes from the wood preservation industry are classified as absolute hazardous (AH). This category includes non-halogenated organic wood preservatives, organochlorinated wood preservatives, organometallic wood preservatives, inorganic wood preservatives, and other wood preservatives containing hazardous substances. In addition, AH wastes cannot be allocated to alternative non-hazardous entries and are hazardous without any further assessment.

The burning of treated wood waste and residues emits arsenic gases, which are highly toxic to the environment (Helsen *et al.* 1998; Helsen and Van den Bulck 2000; Lin and Hse 2005; Nanseu-njiki *et al.* 2007). With regard to landfilling, Jambeck *et al.* (2008) reported that the soil of these sites contained residues and treated wood pieces had elevated concentrations of As and Cr.

One of the first points to note when dealing with the disposal and handling of CCA-treated wood is determining whether the waste is treated wood and whether it should be separated from other sources of untreated wood waste (Helsen and Van Den Bulck 2005). The cited authors claimed that the visual classification of treated wood based on green color is known to be ineffective, although it may potentially reduce the amount of treated wood from the waste pile by approximately 15 to 20%. The effective technologies cited are stains, which could react with treated wood differing from the color of untreated wood, as well as laser and x-ray systems.

According to Kartal and Imamura (2003) and Pan (2010), the development of environmentally friendly technologies for the use of CCA-treated wood waste is of great importance to the environment, to the treating plant, and to the ultimate destination of the product. Therein, the recovery of treated wood prior to handling, reuse, recycling, and disposal can reduce environmental concerns and ensure the safety of the persons involved in the process.

Hawley *et al.* (2012) evaluated the impact of past disposal practices of construction and demolition wastes in groundwater in Florida from February 1992 through February 2007 at C&D and Class III landfills. The database contained 4,534 water quality samples results since 1992 to 2004 from background, detection, and compliance wells. In 2007, the database contained only arsenic results from 88 landfills. Of all landfills, 52 had data from background and compliance wells, and 21 had data of all three well types.

Results indicated that arsenic concentration in the background well was higher than in the detection and the compliance well. The mean for all landfills using the 2004 database for background wells was 9.95 μg/L, whereas for compliance wells it was 7.96 μg/L. Statistics showed there was significant difference in arsenic concentration from the background well (higher) than in the down gradient well. The problem that such findings pose in terms of landfilling is the political decision regarding future management of CCA treated wood, where it must rely on the assessment of future impact caused in these landfills, such as arsenic leaching rate over time and soil natural capacity to immobilize arsenic (Hawley *et al.* 2012). Kartal and Imamura (2003) emphasized that the removal of Cr, Cu, As, and other potential elements of treated wood prior to recycling, reuse, and landfilling is intended to help mitigate contamination of soil and groundwater in landfills and pollution of the air caused by toxic gases released in the burning of these materials.

In order to address these mitigation strategies for contamination, treated wood residues need to be essentially extracted, bioremediated, or separated *via* other decontamination processes to remove toxic heavy metals (Janin *et al.* 2011). Thus, their removal will be essential for the acceptance of the recycled wood into the market.

Techniques for Removal of Heavy Metals from Treated Wood

The objective of a recycling process for the reuse of treated wood involves the extraction of heavy metals such as Cu, Cr, and As from wood and its transfer to a solution (Kartal 2003; Nanseu-Njiki *et al.* 2007; Janin *et al.* 2009, 2011; Chang *et al.* 2012). Figure 3 summarizes the major steps to remove CCA components.

Nanseu-Njiki *et al.* (2007) claims that the reduction of treated wood pieces must take place in order to obtain wood particles of smaller size that can be easily washed with the solution used for the extraction. In addition, when smaller particles of treated wood go through a process of washing with an extracting solution for a certain period, the resulting solution is rich in free particles of the compounds destined for removal that can be used for other purposes.

According to Kartal and Imamura (2003), factors such as wood particle size, diffusion of the chemical in the wood, concentration of the extraction solution, pH, temperature, and extraction time are of great importance in the extraction from the treated wood.

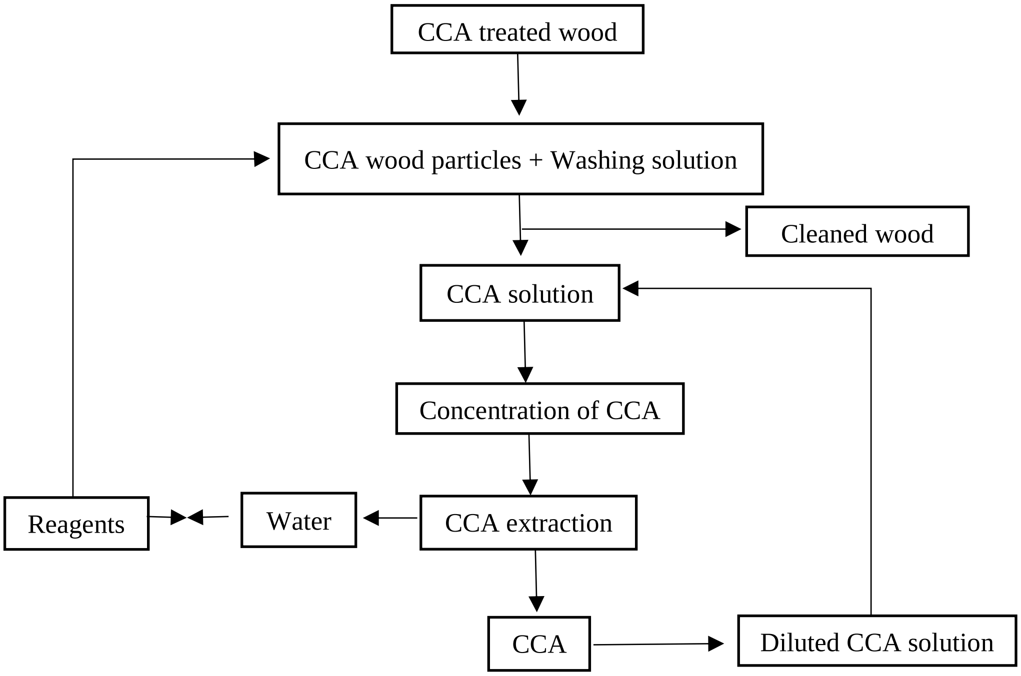

Fig. 3. Steps of the process of CCA remediation. Adapted from Nanseu-Njiki *et al.* (2007)

Other studies have shown that the extraction with acid is the most commonly used method for the removal of the CCA components, mainly due to its efficiency. Table 1 shows some chemical agents, with their best yields, used in several studies for the removal of Cu, Cr, and As. As discussed by Kartal and Imamura (2003), most of the studies pointed out in Table 1 suggested the feasibility in heavy metals removal by using various organic acids, such as citric, acetic, formic, oxalic, ethylenediamine tetra acetic acid (EDTA), fumaric, tartaric, gluconic, malic, sulfuric, hydrochloric, nitric, or phosphoric from treated wood. Chen (2015) pointed out that citrate anion is an effective ligand to the Cu^{+2} complex, and that is why citric acid removed about 100% of Cu and about 90-96% of ammonium citrates.

Table 1. Removal of CCA-treated Wood Elements Using Organic and Other Acids

Agent/Concentration	Extraction time (h)	Residue type	Component removal (%)			Literature
			Cu	Cr	As	
Oxalic acid 1% pH: 2.0	24	Sawdust	81	62	89	Clausen & Smith (1998)
Oxalic acid 1% pH: 2.0	24	Chips	16	14	42	Clausen & Smith (1998)
Oxalic acid 1% pH: 1.7	18	Chips	23	65	74	Kartal & Clausen (2001)
Citric acid pH: 3.5	24	Chips	42	42	38	Shiau *et al.* (2000)
Citric acid 5%	6	Sawdust	99.35	-	-	Chen (2015)
Citric acid 5%	6	Chips	99	-	-	Chen (2015)
Ammonium citrate 5%	6	Sawdust	96	-	-	Chen (2015)
Ammonium citrate 5%	6	Chips	89	-	-	Chen (2015)
EDTA[1] 1% pH: 2.9	24	Sawdust	93	36	38	Kartal & Kose (2003)
EDTA 1% pH: 2.9	24	Chips	60	13	25	Kartal (2003); Kartal & Kose (2003)
EDTA 1% + 1% NTA[2] pH: 1.54	24	Sawdust	67	65	82	Kartal & Kose (2003)
Oleic acid 1% pH:1.4 + 1% EDTA pH: 2.19	24/24	Sawdust	100	90	98	Kartal & Kose (2003)
Oleic acid pH: 2	24	Wood blocks	67	63	81	Gezer *et al.* (2003)
Hydrogen peroxide 2.5%, 90 ºC	2	Sawdust	98	85	78	Kazi & Cooper (2006)
Citric acid pH: 3.5	21 days	Sawdust	81	84	87	Shiau *et al.* (2000)
Pyruvic acid (1.0 g/L) + Lactic acid (1.0 g/L)	4 days	Sawdust	45	25	48	Chang *et al.* (2012)
Oxalic acid 1.0%	8 h	Chips	≈43[3]	≈38	≈3	Clausen (2000)
Oxalic acid 1.0%	24 h	Chips	≈22	≈44	≈20	Clausen (2000)

[1] Ethylenediaminetetraacetic acid. [2] Nitrolotriacetic acid. [3] Approximately equal.

Kazi and Cooper (2006), effectively extracted most of the components of treated wood using hydrogen peroxide in short extraction time. Kartal and Imamura (2003) showed that high concentrations of humic acid increased Cu and Cr leaching from CCA-treated wood.

Kartal and Imamura (2003) also mentioned that extraction using acidic solutions featured higher efficiency on the preservatives removal and that the time of extraction could be minimized by adjusting the temperature and concentration of the removing agent. Another way to increase the removal efficiency is using double extraction cycle on the same treated wood sample.

Shiau *et al.* (2000) showed that citric acid extraction not only removed high quantities of heavy metal, as denoted in Table 1, but they also showed a steep heavy metals removal when pH dropped from 5.0 to 3.5 for Cr and As. For instance, citric acid extraction over 21 days could extract 47% of Cr at pH 5 and 81% at pH 3.5. Regarding As, 72% was removed at pH 5 and 87% at pH 3.5. The authors stated that the acidic environment may have a key role to support the leaching of CCA chemicals.

One of the barriers to chemical extraction methods is the high concentration and volumes of chemicals used for the extraction and the need for several stages to ensure the removal of the preservative chemical components. Thus, technology to recover the extracted products is not yet commercially feasible (Helsen and Van Den Bulck 2005). The same authors also claimed that future research would be needed to improve and evaluate the process of chemical extraction. Studies would be needed to assess, for example, the effect of extractions on the energy properties and other properties of particles recovered.

Another alternative for the removal of the preservative chemical components from spent treated wood is known as bioremediation. According to Kartal and Imamura (2003), the bioremediation of treated wood and its residues involves complex biological, chemical, and physical reactions, where the process is able to mobilize heavy metals. Various organisms have been recognized by the ability of either oxidation or reduction of heavy metals in water-soluble form such as, Cr, Cu, and As, which can be removed from the treated wood (Kartal and Imamura, 2003).

According to Clausen and Smith (1998) and Clausen (2004), bacteria do not achieve high efficiency in the removal process due to the Cr removal limitation; however, the use of bacteria has been shown to be effective in the removal of Cu and As. The cited authors claim that a two-step remediation would be necessary to enhance CCA removal. This two-step remediation uses a combination of acids and bacteria medium. In his work, the two-step remediation reached removal of 21% Cu, 54% Cr, and 63% As. The non-bacteria medium removal, reached only 17% Cu and 15% As, without chromium results

Clausen (2000) performed a two-step remediation of CCA-treated wood wafers. The first step has been the removal of the elements using oxalic acid and the best yields for each element are described in Table 1. The second step constituted in combining the best acid oxalic removal (1.0%) with cultures of *Bacillus licheniformis* CC01 for seven additional days. When the two-steps were combined, 18 h yielded the best general removal, with Cu removal from about 30% to 70%, Cr from about 40% to 80%, and As from about 3% to 90%.

Clausen (2004) studied the use of heavy metal tolerant bacteria *Bacillus licheniformis* using a less concentrated culture medium (1.0%) and a wood to nutrient medium ratio of 1:10. In this study, 17% Cu and 15% As removal were reached. When oxalic acid extraction preceded bacterial remediation, removal of the elements were 21%, 54%, and 63% for Cu, Cr, and As elements, respectively. Although, the two-step process was effective in removing heavy metals, it was relatively costly.

Chang *et al.* (2012) extracted CCA heavy metals using a two-step processing procedure with the bacteria *Lactobacillus bulgaricus*, *Lactobacillus acidophilus*, *Lactobacillus plantarum* and, *Streptococcus thermophilus* as removing agents on chip samples from southern yellow pine. In the first step, a maximum of 72% of As, 65% of Cu, and 55% of Cr were extracted from the samples. In the second step, 92% of the As, 80% of the Cu, and 70% of the Cr that remained after the first step was also extracted. The initial analysis for metals content was 6.41 mg/g for Cu, 4.13 mg/g for Cr, and 3.26 mg/g for As. Although satisfactory results were found, further studies will be needed before implementation of a larger-scale CCA extraction.

Some wood preservatives are not accessible for public use due to identification of risks in occupational exposure (*i.e.* treating plants) by EPA, although they can be used in the railroad industry, utility poles, and pilings. One of these wood preservatives is pentachlorophenol (PCP) and inorganic arsenic compounds (Lebow 2010).

Lamar and Dietrich (1992) evaluated the lignin-degrading fungal species *Phanerochaete chrysosporium*, *P. sordida*, *Trametes hirsuta*, and *Ceriportopsis subvermispora* for their ability to decrease the concentration of PCP in chips from hardwoods and softwoods. Results indicated that *P. chrysosporium* or *P. sordida* resulted in decreases in PCP as high as 72% after 6 weeks. However, there were no statistically significant differences between hardwoods and softwoods. The reductions were even accentuated when the strain of *T. hirsuta* was inoculated, where there was a decrease of 84% in PCP concentration. For *C. subvermispora* the decrease in concentration was 37%, the least of any fungi assessed. The authors argued that once the protective barrier of wood is disrupted (chipping), the untreated wood is exposed such that the fungi have the capacity of depleting PCP.

Although the literature suggests that bacteria do not achieve high efficiency in the removal process of Cr, it has a remarkable effect on creosote and PCP (Portier and Miles 1996). Chemical and biological methods were performed. The chemical method was constituted of alcohol extraction and the biological one used bacterial strains from the genera *Pseudomonas*, *Flavobacterium*, and *Acinetobacter*. An initial creosote concentration of 29,000 ppm was reduced to a mere 95 ppm when the chemical method was used. The biological method removed 91% of the 95 ppm remaining, leading to a mere 8 ppm creosote concentration, whereas PCP initial concentration was 1,190 ppm before and only 2 ppm after both methods and the differential between methods was not attempted.

Production of enzymatic systems such as pectinolytic and cellulolytic from *Bacillus* and *Pseudomonas* genera may assist in releasing Cu, Cr, and As from wood (Clausen and Smith 1998). In addition, it has been suggested that bacterial capsules or slime layers complex with elements by releasing them enzymatically in small quantities (Greaves 1971). It also was suggested that the mechanisms involved in bacterial metal resistance result from the active efflux pumping of the toxic metal, or the enzymatic detoxification, converting a toxic ion into a less toxic or less available metal ion (Mejare and Bulow 2001).

Unligil (1968) reported on the tolerance to pentachlorophenol strains of fungi on malt agar medium. Pine sapwood blocks were impregnated and exposed for 52 days to *T. viride* and *C. puretana*. Analyses of wood block revealed that a substantial part of the loss of PCP from wood block was due to fungal activity without causing appreciable weight loss; 62% of PCP from samples containing 5.8 kg m^{-3} were depleted by *T. viride*, whereas *C. puretana* was able to deplete about 55% from samples containing 5.2 kg m^{-3}.

Kartal *et al*. (2004) pointed out that brown-rot fungi (*Aspergillus niger*) can also be used for the bioremediation process of CCA-treated waste wood. The oxalate produced by these types of fungi have the ability to react with ions, thus suggesting the use of these fungi for the remediation of treated wood. They also claimed that the amount of oxalic acid produced by these fungi appears to correlate to why some of these decay fungi display Cu tolerance. The results showed that *A. niger* fermentation removed 49% Cu and 55% Cr from the treated wood.

Kartal *et al.* (2015) studied the copper bioremediation of ground wood treated with alkaline copper quaternary (ACQ), micronized ACQ, nano-CuO, and CCA-C using fungi such as *Tyromyces palustris*, *Coniophora puteana*, *Gloeophyllum trabeum*, and *Postia placenta* (brown-rot fungi); several strains of *Serpula lacrymans* (dry-rot fungus); *Trametes versicolor*, *Pleurotus ostreatus*, *Irpex lacteus* (white-rot fungi), and *Aspergillus niger* (mold fungi). Results indicated that brown-rot fungi released about 70% copper from nano-CuO, with a similar trend of removal for ACQ and micronized ACQ. High Cu releasing was found by *S. lacrymans*, where it was able to mobilize as high as 90% of the Cu from nano-CuO and ACQ. However, Cu removal from CCA samples was relatively low when compared to ACQ. This is important, once most treated wood present at disposal sites are CCA-treated wood. The fungus *A. niger* was able to bioremediate Cu less than brown-rot fungi and more than white-rot fungi, where nano-CuO reached the smallest Cu removal.

Helsen and Van Den Bulck (2005) pointed out that the biological extraction of treated wood allowed almost complete extraction. They recommended that the combination of solvent extraction using the two-step remediation method should also be used. In addition, they emphasize that some restrictions limit the use of this method. Although it is technically feasible, it is a relatively slow and presents a high cost due to the high cost of the nutrients of the culture medium.

Polcaro *et al.* (2008) proposed a bioremediation system for creosote-treated wood based on the detoxifying capability of *Pleurotus ostreatus*. Results indicated that almost complete degradation of creosote oil components took place after 44 days by reducing ecotoxicity. Phenols compounds were completely degraded in the bioremediation proceeding, whereas polycyclic aromatic compounds were almost detoxified with rate of 90% of efficiency.

Kartal *et al.* (2015) evaluated the bioremediation and decay of wood treated with ACQ, micronized ACQ, nano-CuO, and CCA wood preservatives. Results indicated that brown-rot fungi including dry-rot fungi caused more Cu removal in comparison with white-rot fungi. They also suggested that grinding treated wood to sawdust accelerated the remediation; however, longer fungal remediation process durations may be needed when compared to chemical extractions.

In a study conducted by Saritha *et al.* (2010), two unidentified fungi were isolated from soil and marine environment and used for remediation of pulp and paper mill effluent at laboratory scale. The isolated fungi strains were able to decompose the lignin and cellulose complex from pulp and paper. In fact, the treatment resulted in the reduction of color, lignin, and chemical oxygen demand in the order of 78.6%, 79%, and 89.4%, respectively, in 21 days.

The fungal mechanisms to remove heavy metals are associated with enzymatic systems, where, in some cases, the fungus' hyphae penetrates the cell wall and excretes enzymes, which are responsible for dissolving the metals (Felton and De Groot 1996; Kartal and Imamura 2003). The remediation with fungi can be reached when the strain has metal catabolic activity and the ability to transform the metal by bringing it to a lower concentration (Alexander 1999). In fact, Felton and De Groot (1996) affirmed that microbes degrade toxic metals from penta, creosote, and CCA, and these metals need to be in water-soluble form.

Despite all of the technology developed to extract metals from treated wood by chemical and/or biological agents with both reaching environmentally friendly outcomes compared to the common disposal, and even after production of several US patents, as n° 6,495,134 and 6,972,169 for remediation of CCA; 6,383,800 and 6,727,087 for pentachlorophenol; 6,387,689 for creosote and 6,387,691 for ACQ in the early 2000's, it seems that remediation of treated wood demands clearer laws. Specifically, laws could clarify this topic so that such that companies and the public would be encouraged to use alternative methods to dispose of such wood. Ultimately, the cost and labor intensive method used in chemical agents and the time needed to accomplish biological removals does not seem to compensate the remediation advantages, leading to continuous incineration, burning, disposal at construction sites, and landfilling.

CONCLUSIONS

There is a growing concern about the reuse and recycling of CCA-treated waste wood, and attention must be given because it has a defined service life. Thus, environmentally friendly and cost effective alternatives to the detoxification of treated wood waste are needed.

Treating wood waste by subjecting it to acid extraction at optimum temperatures and concentrations plays a promising role in the removal of the main chemical components from the preservative products contained in wood waste. However, the pre-chemical extraction of the residues and the subsequent bioremediation seem to be an efficient alternative for the removal of high concentrations of heavy metals in the treated wood.

Attention must be paid to the use of bioremediation, as some of the organisms do not have high efficiency or may not assimilate some compounds such as Cr. In addition, researchers must look for alternatives regarding the cost of this method, because the use of large amounts of culture media represents a financial limitation.

The processes of chemical extraction and bioremediation of CCA-treated waste wood have a number of environmental advantages in comparison to the burning of treated wood and its deposition in landfills. Progress of studies on these processes is of great importance to generate correct alternatives and reliability for the use of waste from the treated wood.

Projections indicate that the production of waterborne treated wood will increase, with a decreasing rate in its disposal. However, this decline is expected to be gradual, which would demand more governmental incentives and public awareness of the issue when treated wood is disposed. Another point is that most of the treated wood is not disposed as sawdust or chips, but rather, with reasonable dimensions. Future research needs to address larger-scale bioremediation methods with technology to reduce fungal processing time, media, and chemical reagents costs, taking into account the treated wood dimension found at disposal sites.

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