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Bacterial Associations with Decaying Wood: a Review

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Wood-inhabiting bacteria are associated with wood decay and may have an indirect influence on the decay process. Bacteria are able to affect wood permeability, attack wood structure, or work synergistically with other bacteria and soft-rot fungi to predispose wood to fungal attack. Bacteria that can inhabit chemically treated wood are recognized. The natural ability of certain bacterial genera to decompose creosote, mineralize pentachlorophenol, and tolerate chromated-copper-arsenate (CCA-)-treated wood is discussed with respect to their role in the biodegradation of chemically preserved waste-wood products. Published by Elsevier Science Limited.

INTRODUCTION

The association of bacteria with wood has been recognized since the 1950s and 1960s. Little attention has been given to the effects of bacteria on deterioration of wood compared with the extent of degradation caused by wood decay fungi. Lack of mobility restricts the bacterial mode of attack, prolonging the process of wood cell wall deterioration (Rossell *et al.,* 1973). Notably, bacteria are the most numerous and ubiquitous of organisms. They are capable of colonizing wood under both aerobic and anaerobic conditions. Most research has addressed structural changes in wood caused by bacteria or the presence of bacteria in preserved wood which has succumbed to failure. Even then, bacteria were typically associated with soft-rot fungi. In the latter instance, research emphasis was directed solely towards preventing future failures of treated wood (Duncan & Lombard, 1965; Petrenko, 1969; Baecker, 1993; Eaton, 1994).

The association of bacteria with wood degradation has been briefly visited and revisited since the 1960s by a small number of researchers. One pioneer in this area, Greaves (1971), classified bacteria involved with wood degradation into groups, depending on the role they play in wood decay: (1) those that affect permeability but cause no strength loss; (2) those that attack wood structure; (3) those that work synergistically with other bacteria to breakdown wood; and (4) passive colonizers that may be antagonists to other bacterial populations. This review looks at the first three groups of bacteria with respect to their role and capacity in the biodegradation of treated wood.

Organisms from the three groups classified by Greaves act in a varied and integral manner that contributes directly and indirectly to the wood decay process. Bacteria and actinomycetes are probably the most common wood-inhabiting microorganisms and the initial colonizers of wood. They are part of a succession of microorganisms that may act synergistically with fungi to either contribute to the breakdown of wood or remove compounds that may be toxic to decay fungi. Blanchette *et al.* (1978) reported that bacteria and yeasts were found to have a mutualistic association with white-rot fungi. During the initial invasion of wood, there is most likely a succession of bacteria before fungal wood inhabiters take their place in the overall succession of microorganisms (Rossell *et al.,* 1973; Shigo & Hillis, 1973).

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PERMEABILITY

Structural changes in wood caused by bacteria were thought to have a rather lengthy incubation period, with noticeable damage taking years to occur (Courtois, 1966; Liese & Karnop, 1968). Schultz (1968) found that 4–6 weeks was sufficient time to increase permeability of wood, although degradation of wood structure was not detected. Maltern (1969) also demonstrated that bacteria could completely penetrate wood structure in 4–6 weeks. It has long been known that water-logged wood is inhabited by a mixed bacterial population, which alters the permeability of wood (Jutte, 1971). Frequently, bacterial inhabitation of wood causes striking increases in permeability to liquids (Rossell *et al.,* 1973). Increasing permeability can be either beneficial by aiding in pressure treatment of lumber or a hindrance by causing overabsorption of organic preservatives during dip treatments (Rossell *et al.,* 1973). A review by Fogarty (1973) addresses the important role bacterial pectinase plays in increasing wood permeability, and therefore penetration of wood preservatives, for commercial purposes. Knuth and McCoy (1961) isolated *Bacillus polymyxa* from wood that displayed excessive absorption of solvent. The extreme porous conditions resulting from treatment of sound pine with *B. polymyxa* were believed to be a result of hydrolysis of pectic compounds and possibly hemicellulose and cellulose (Greaves, 1971; Rossell *et al.,* 1973).

STRUCTURE

There is general agreement that bacteria cause no striking destruction of wood. However, conflicting opinions exist on the importance of the role of bacteria in the overall decay process. Bacteria observed attacking the wood structure are often referred to as either erosion or tunnelling bacteria.

Tunneling or cavitation decay patterns were first described by Nilsson and Daniel (1983) and Nilsson and Singh (1984). This type of bacterial decay is characterized by distinctive troughs seen under TEM. Holt (1983) used SEM to distinguish bacterial cavity formation from bacterial erosion patterns. Bacteria responsible for these phenomena were initially undescribed, because they could not be cultured in the laboratory and the decay pattern, often associated with fungal decay, was thought to be an aerobic one. Utilizing strict anaerobic techniques, Rogers and Baecker (1991) first isolated and identified *Clostridium xylanolyticum,* one bacterium responsible for tunneling decay. Most studies involving bacteria associated with wood biodeterioration have been conducted aerobically. Even studies on obligate anaerobes have traditionally not been conducted under strict anaerobiosis. Strict anaerobes were thought to invade wood only in aqueous environments. Work by Nilsson and Daniel (1983) and Rogers and Baecker (1988) resulted in the theory that there are anaerobic microniches in wood structure caused by respiratory depletion of oxygen by indigenous aerobic microorganisms. The redox potential is lowered appreciably within the microniches, creating zones ideally suited for anaerobes. Collectively, these findings shed new light on the potential role of anaerobes in the biodeterioration of wood, even in an aerobic environment. Tunneling was also demonstrated by Baecker and Rogers (1991) using immunolocalization with colloidal gold and electron microscopy. Nilsson and Daniel (1983) and Singh *et al.* (1987) described a pattern of tunneling decay in which the S_3 layer of the wall was penetrated. Penetration of wood is typically limited to the outer 1 cm, so that transport and dispersal of the invading organism must rely on motility, transport by an aqueous environment, or synergistic effects of multiple enzymes upon wood cell wall penetration (Greaves, 1971).

Decay patterns caused by erosion bacteria are characterized by various formations observed under TEM, including depressions, channels, and honeycomb patterns (Singh *et al.,* 1994). Less is known about wood degradation by erosion bacteria than about tunnelling bacteria, but erosion bacteria exhibit some interesting characteristics with respect to the role of bacteria in deterioration of treated wood. Erosion bacteria can degrade wood under conditions that would inhibit both growth and activity of wood decay fungi, that is, conditions of little or no oxygen such as waterlogged environments (Singh & Buther, 1985; Singh *et al.,* 1990, 1992; Kim & Singh, 1993; Singh & Wakeling, 1995). Erosion troughs can be divided into two types: (1) shallow, surface erosions in the tertiary lamella or S_3 layer, which are mainly caused by bacilli; and (2) deep troughs that progress from the lumen to the secondary cell wall and occasionally into the middle lamella, which are mainly caused by cocci (Greaves, 1971). Both types of erosion have been seen simultaneously. Recently, erosion bacteria were found to be present in chromated-copper–arsenate (CCA)-treated timbers, Not only

was it the main type of degradation present in the failed poles, but attack by erosion bacteria was throughout the diameter of the pole, while attack by soft-rot fungi was confined to outer areas of the pole (Singh *et al.,* 1994).

The powerful cellulolytic and pectinolytic enzyme systems of bacteria are believed to play an important role in the structural changes in wood (Grosu *et al.,* 1973). *Bacillus polymyxa* is able to hydrolyze pectin and holocellulose (Knuth & McCoy, 1961). *Clostridium xylanolyticum,* the tunnelling bacterium, produces a potent xylanase (Rogers & Baecker, 1991; Baecker & Rogers, 1991). Hardy (1970) suggested that cellulolytic and pectolytic bacteria begin wood breakdown by colonization of ray cells. Ray cells are the main source of nutrients for invading bacteria (Greaves, 1969, 1970, 1971). Bacterial cellulases alter the permeability of wood, opening up the crystalline arrangement of the cellulose as a target for advanced diffusion of cellulolytic enzymes (Greaves, 1971). Boutelje and Bravery (1968) demonstrated that *Bacillus polymyxa* affects the crystalline structure of cellulose microfibrils by the diffusion of cellulases some distance from the bacterial cell. It is believed that they derive nutrients present in the wood cell wall or deposited on the S_3 layer of the secondary wall. Particular organisms implicated in this process are *Bacillus polymyxa, Pseudomonas* sp., and *Ciostridium* sp. Cellulases from *Bacillus polymyxa* (Greaves & Levy, 1965) diffuse freely from their site of production, are able to move across the S_3 layer of the cell wall, and alter the crystalline structure of cellulose microfibrils in the S_2 layer, as noted by a marked alteration in their birefringence pattern under polarized light (Greaves, 1969, 1971; Greaves & Levy, 1968; Boutelje & Bravery, 1968). Greaves postulated that advanced diffusion of bacterial cellulases emulated brown-rot decay. Altering permeability of the S_3 may be a key to infiltration of fungal enzymes that are otherwise too large to enter wood structure. The endoglucanase of the bacterium *Cellulomonas* is reported to influence fiber size of Avicel (Poulsen & Petersen, 1992). Although those bacteria solely altering wood permeability show no effect on wood strength (Ellwood & Ecklund, 1959), the group of bacteria that attack wood structure causes a distinct reduction in compression strength, bending strength, and modulus of elasticity (Boutelje & Bravery, 1968).

SYNERGISTIC EFFECTS

Structural changes and altering permeability may predispose wood to further bacterial and fungal attack. Bacterial pectinases attack the membrane of the bordered pit, causing complete degradation of the pit membrane (Liese & Bauch, 1967). Greaves (1969) reported complete erosion of the secondary cell wall of fibers and tracheids by bacteria. Paserin (1970) reported that wood stored under water longer than 4 months was predisposed to fungal attack. The mixed bacterial population in waterlogged wood hydrolyze cellulose and hemicellulose (Greaves, 1971; Rossell *et al.,* 1973). Aside from synergistic effects of bacterial cellulases, hemicellulases and pectinases on wood cell wall degradation by fungi, dead bacterial cells may provide a valuable source of nitrogen, a most important fungal nutrient that occurs in very low concentrations in wood; C/N ratios are as high as 350:1. Fungi may overcome N_2 deficiencies by translocating the element from surrounding soil where it is accumulated by N_2-fixing bacteria (King & Waite, 1979). Nitrogen-fixing bacterial species associated with wood decay have been reported (Seidler *et al.,* 1972; Aho *et al.,* 1974; Larsen *et al.,* 1978; Spano *et al.,* 1982; Jurgensen *et al.,* 1984). King *et al.* (1980) suggested that bacterial counts in wood equal to counts commonly found in soil or decayed wood contribute significantly to nitrogen estimates of wood during decay. Soil bacteria can increase the nitrogen of timber in ground contact (Levy, 1975). Soil also contains sulfate-reducing bacteria, which are responsible for movement of iron into wood; naturally occurring iron in wood is insufficient to stimulate fungal growth (Ruddick & Kundzewicz, 1991). Capsules or slime layers in certain bacteria may serve as sugar reserves for the succession of fungi. It was postulated by Hardy (1970) that bacteria accumulate metabolic by-products, which are utilized as growth factors for invading fungi.

Wood in ground contact provides a suitable substrate for soil bacteria to grow on, and it is at ground contact that bacterial attack usually begins (Rossell *et al.,* 1973). Etheridge (1961) postulated that bacteria were the primary colonizers of wood in ground contact followed by fungi. Hawker *et al.* (1960) noted that many soil bacteria are able to hydrolyze cellulose and hemicellulose. Oxalic acid, produced by brown-rot fungi. is deposited as calcium oxalate in wood attacked by brown-rotters and in soil. Fungi are able to liberate calcium from

calcareous materials such as glass, concrete and mortar, and utilize it to inactivate excess oxalic acid as water-insoluble calcium oxalate (Bech-Anderson, 1987). According to Chandra and Shethna (1975) bacteria, such as *Pseudomonas oxalaticus* and *Bacterium oxalatum*, utilize calcium oxalate from soil as a source of carbon and calcium. The sequestering and release of calcium is one possible synergistic relationship between fungi and bacteria in the complex sequence of events initiating wood degradation.

TREATED WOOD

Since the 1950s, bacterial inhabitants of preservative-treated wood have been recognized, but research has always emphasized wood-inhabiting Basidiomycotina. Most concern has surrounded extending the service-life of treated wood against a few chemically resistant soft-rot fungi. Few papers have been devoted to the decomposition of preserved wood (Greaves, 1968; Greaves & Savory, 1965; Petrenko, 1969). Drisko and O'Neill (1966) identified a species of *Pseudomonas (P. creosotensis)* that decomposed creosote. Pseudomonads possess strong enzyme activities and a marked capacity for ammonification, making them a noted part of the bacterial flora of preserved woods. Nonspore-forming *Pseudomonas* spp. are commonly replaced with spore-forming *Bacillus* spp. in the succession of species. Members of both genera have the ability to attack wood treated with oil-based preservatives, such as copper naphthenate and pentachlorophenol, and are more resistant to copper than Basidiomycetes. Eaton and Hale (1993) and Eaton (1994) identified tunnelling bacteria as the source of decay of ammoniacal-copper-quaternary-ammonium (ACQ-)-treated wood in water cooling towers. A more recent review addresses the detoxification of preservative-treated wood (Schmidt & Liese, 1994).

Chemical wood preservatives are targets of environmental concern and will likely be replaced as soon as more benign alternatives become available. However, disposal of chemically treated wood will continue to be a problem for decades. Disposal of CCA-treated wood is a particularly difficult problem because incineration concentrates the toxic metals. Likewise, options for disposal of pentachlorophenol (PCP-)-treated wood are limited; PCP-treated wood maintains close to the original retention of the chemical after an expected service life of 50+ years (McBain *et al.,* 1995). Bacteria are often able to tolerate preservatives at retention levels usually employed to prevent fungal attack (Shields, 1969). Increased quantities of preservative hardly change the overall bacterial flora. Rather, under those circumstances, the flora is naturally supplemented with more cellulolytic bacteria. Also, high loadings of preservatives indirectly enhance bacterial populations by excluding fungal competitors.

There are few published reports of bacterial growth in the presence of wood preservatives, despite numerous descriptions of the bacterial effects on treated-wood structures. Schmidt and Liese (1974) and Schmidt *et al.* (1975) examined the bacteriocidal effects of commercial wood preservatives and their components on *Bacillus subtilis, Cellulomonas* sp., *Erwinia carotovora, Serratia marcescens* and *Pseudomonas convexa.* They reported sensitivities similar to a group of fungi tested with the same preservatives, but bacteriocidal concentrations were much greater than bacteriostatic concentrations. They also found that pentachlorophenol, chromium and copper were much more effective at inhibiting bacterial growth than boron or fluorine. Recently, Greaves (1973) looked at the uptake of CCA components by *Bacillus subtilis, Pseudomonas aeruginosa* and *Streptococcus salvarius* isolated from preservative-treated wood. He found that CCA was bacteriostatic rather than bacteriocidal at concentrations as high as 0.675%. All strains remained viable, even though growth was completely inhibited. Greaves theorized that CCA affects bacterial cell membrane permeability, which in turn causes growth inhibition. Fungal and bacterial tolerance of CCA varies with the amount of preservative present in the wood and the service conditions (Singh *et al.,* 1994).

It has been theorized that bacterial capsules and slime layers complex with elements such as copper and 'lock up' the toxic metal when it is released in small quantities by bacterial enzymes. In this form, the copper would be nontoxic to wood decay fungi (Greaves, 1971). Daniel and Nilsson (1985) and Daniel *et al.* (1987) found copper accumulation as dense particles within the nuclear region of tunneling bacteria, while a majority of Cr and As remained in extracellular secretions. Henningsson (1967) isolated a wood-inhabiting bacterium that greatly accelerated the decomposition caused by wood decay fungi on wood

impregnated with sodium pentachlorophenol. This was probably due to the widely occurring ability of bacteria to split phenols, thus detoxifying the preservative. Certain bacterial species remove or detoxify preservatives, such as copper and chromium, to pave the way for invasion by fungi (Hochman, 1967; Greaves & Foster, 1970; Rossell *et al.*, 1971). *Pseudomonas creosotensis* is a prime example of a bacterial detoxified of creosote and phenolic structures (Hochman, 1967). Schmidt *et al.* (1991) investigated the biodegradability of creosote by bacteria and reported that *Aeromonas hydrophila, Flavobacterium* sp., and three species of *Pseudomonas* were able to grow in the presence of creosote. Both pure and mixed cultures of fungi and bacteria are able to degrade PCP. Parameters have been worked out and utilized in the degradation of PCP in water and soil (Crawford & Mohn, 1985; Valo *et al.*, 1985), but their abilities have just been recognized in the mineralization of PCP in treated wood products (Briglia *et al.*, 1994; Yu & Ward, 1994). Species of *Flavobacterium* have been isolated that can utilize PCP as their sole source of carbon (Saber & Crawford, 1985). These organisms degrade more than 99% of the PCP extracted as a water soluble salt from sawdust or wood chips (McBain *et al.*, 1995). The fate of preservative elements released from the mineralization of treated wood causes environmental concerns (Baecker, 1993). Environmental regulations on the release of chlorinated organics in pulp mill effluent eliminates pulping as a means of disposing of PCP-treated wood (McBain *et al.*, 1995). Biological degradation of PCP to harmless inorganic end products is a viable alternative (Valo *et al.*, 1985).

Thermophilic and thermotolerant bacteria are prominent in chip piles where temperatures as high as 45-50°C inhibit the growth of Basidiomycetes, while thermophilic bacteria can flourish. Eslyn (1967) investigated the rate of decay of pulpwood chip piles and showed that microorganisms in the outer layers (25°C) differ from those in the interior of the pile (45°C). Bjorkman & Haeger (1963) and Henningsson (1967) found bacteria in the outer layers of chip piles to be in association with fungi. Degradation of shavings and sawdust may be accelerated by enrichment with thermophilic and cellulosic bacteria. Preservative-tolerant bacteria may be able to precondition treated chips or mineralize toxic elements for environmentally safe disposal or recycling of treated wood waste.

CONCLUSIONS

Evidence that bacteria act in a varied and integral manner during the process of wood biodeterioration has been presented. Initial colonization of wood by bacteria or a succession of bacteria increases permeability of wood structure by penetration of the bordered pits and S_3 of the wood cell wall and predisposes wood to fungal attack. The natural ability of certain genera of bacteria to tolerate chemical preservatives at levels that inhibit fungal growth, either by detoxification or mineralization, may prove beneficial in the environmentally safe disposal of chemically preserved waste-wood products.

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