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Review

Hygienic Perspectives of Wood in Healthcare Buildings

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Abstract: Wood materials are being adopted as nature-based architectural themes inside the healthcare buildings. Concern is raised that the organic and porous character of wood might support microbial survival. Therefore, this review discusses the hygienic properties of wood including the antimicrobial potential and its cleanability in comparison to smooth surface materials. In general, wood has antimicrobial properties owing to its chemical composition and physical structure. However, the hygienic potential of wood is influenced by the type of wood, age of wood, the cleaning method, surface treatment, and its moisture content. This information is intended to guide decision-makers regarding the use of wood in hygienically sensitive places and researchers to help them identify the variables for better utilizing the hygienic potential of this material.

Keywords: surface hygiene; wood; antimicrobial; biofilms; green buildings

1. Introduction

The construction of hospitals and other healthcare facilities has a significant impact on the environment in terms of material usage and consumption of energy and waste generation [1]. Therefore, sustainable construction of healthcare buildings demands the use of eco-friendly materials which can be recycled and have low embodied energy and environmental impact [2,3].

The occupants of healthcare buildings including the patients and the staff, have a higher level of stress as compared to general populations [4]. In the patients, stress is mainly linked to the illness, while for the staff is linked to long working hours and the need to take life-saving decisions [4]. Past research has shown that the interior environment could reduce the level of this stress in the hospital building occupants [5]. One of the main modifications is the use of nature-based architectural themes which provide a healing and relaxing environment to the patients and the staff of healthcare buildings [6].

Wood is an organic and renewable resource of nature that is abundantly used for eco-friendly constructions and is an important component of nature-based themes [7].

Therefore, using wood material in the construction and designing of healthcare buildings can contribute to the reduction of stress in occupants and the improvement of sustainability markers of healthcare buildings [1,8]. This is the reason that the growing number of healthcare buildings are adapting this material.

There is still hesitancy in widely adopting wood for indoor applications in healthcare buildings because this material is perceived as unhygienic owing to its porosity and organic nature [9]. However, some research has shown that untreated wood materials have antimicrobial properties against a wide range of pathogens responsible for healthcare-associated infections (HAI) [10]. Moreover, the most common microbes, including the SARS-CoV-2, survive least on porous materials as compared to smooth solid materials [11–13]. Meanwhile, the cleanability of wood is no worse than other materials such as plastic, glass, and steel [9].

This literature review aims to gather knowledge on the potential uses of wood material in healthcare buildings. It discusses the antimicrobial and hygienic properties of wood along with the influencing variables. This information is intended to identify the knowledge gaps and provide guidelines to the stakeholders regarding the hygienically safe uses of wood in healthcare buildings.

2. Wood as an Indoor Material for Healthcare Buildings

Wood, as indoor material, is generally used for two purposes, i.e., construction and aesthetics, and mostly both go along together, for example, in making furniture, floors, ceiling, and walls [14]. The structure may involve untreated wood, however, a treatment is often applied to protect against wood degrading pests and fungi depending upon the type of wood, geographic location, and the desired look. Indoor surfaces of wood are also frequently coated to protect them from scratches, stains, and weathering [15]. Indeed, various chemicals are used for processing of wood, such as adhesives, pesticides, solvents, resin binders, waterproofing compounds, stains, pigments, paints, and varnishes [9,16]. Some of these chemicals can be toxic [17], as some countries allow the use of, creosote, pentachlorophenol (PCP), or chromated copper arsenate (CCA) [18]. In addition, various volatile organic compounds (VOC) are emitted during such treatments (wood processing) and can cause respiratory or other health-related issues/illnesses. Therefore, nontoxic compounds are favored for wood treatments [18].

Therefore, in this review, we mostly discuss 'untreated wood', which is free from surface treatment and coating, because this condition best represents the natural properties of wood. In addition, the application of surface finishes could make wood materials more difficult to recycle. Although some studies discuss the antimicrobial properties of wood coatings [19,20], that is a different subject. In addition, untreated wood is sometimes used as an indoor material in form of non-contact furniture surfaces, ceilings, floors, and some wall frames. Such untreated materials are more preferred to be recycled as compared to treated wood.

3. Healthcare-Associated Infections (HAI) and Role of Environmental Surfaces

Nosocomial or healthcare-associated infections (HAI) are transmitted to patients when they receive medical care in healthcare facilities. The World Health Organization (WHO) remarks HAI as the most common adverse event among hospitalized patients [21]. In general, the HAI concern up to 7% of the hospitalized patients in developed and 10% in developing countries [22]. They are responsible for increasing the economic burden on the healthcare system by prolonged hospital staying time, disability, and treatment cost [23,24].

Generally, HAI are characterized as ventilator-associated pneumonia (VAP), central line-associated bloodstream infections, catheter-associated urinary tract infections, and surgical site infections [25]. The severity of these infections can range from mild to fatal depending upon the causative microorganism, e.g., bacteria, fungi, or viruses, and the type of infection or system infected.

The prevalence of these microbial agents differs depending upon patient populations, available medical facilities and the condition of the indoor environment. The most notable etiological agents causing HAI can be listed as: *Staphylococcus aureus*, *Enterococcus* spp. (e.g., *E. faecalis*, *E. faecium*), *Escherichia coli*, *Candida* spp. (e.g., *C. albicans*, *C. glabrata*), *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*, *Acinetobacter baumannii* and *Aspergillus fumigatus* [26]. The viruses are also very important in the context of HAI, especially, the seasonal influenza virus, and the recent Severe Acute Respiratory Syndrome associated Coronavirus (COVID-19 virus).

Environmental surfaces are the non-clinical items including medical devices (catheters, surgical instruments, stethoscopes, electronic thermometers, blood pressure cuffs, infusion pumps, hemodialysis machines, etc.), and the household surfaces of the patient room, washroom, and surrounding objects (Figure 1). The household surfaces can be further classified based on the frequency of touch as the high contact (bed railings, sink, tap, door handle, curtain, etc.), medium contact (furniture, window frame, floor, etc.), and low contact surfaces (ceilings, walls, pillars, etc.) [27].

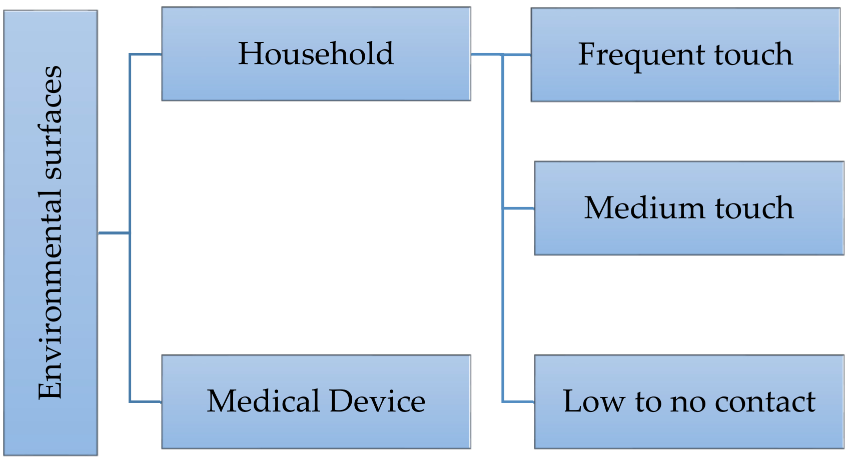

Figure 1. Classification of indoor environmental surfaces in healthcare buildings.

Environmental surfaces inside healthcare buildings could be a reservoir of infectious agents and can play a role in transmission (Figure 2). Primarily, patients contaminate the environmental surfaces when they directly touch them [22,28]. Meanwhile, the settling down of sneezed and coughed droplets can also contaminate surfaces [29]. Some aerosol particles generated during washing and toilet flush can also contaminate the surrounding surfaces [30]. These environmental surfaces are a continuous risk as long as the contaminating microbes survive on them, and this survival time can be short, from minutes, to long, for months, [31] depending upon the type of microorganism and the surface material (Table 1). The transmission occurs when a susceptible individual comes in contact with these contaminated surfaces [27,32]. Healthcare personnel's hands can also get contaminated from surfaces and pass pathogens to susceptible patients [32].

Low to non-contact surfaces, such as ceilings, walls, floors, window frames, and some furniture are not considered as an important source of microbial transmission. Therefore, they are not cleaned as often as the frequent contact surfaces [33]. However, they may sustain the microbes and can result in transmission by accidental contact, or by indoor air contamination during cleaning, construction, and renovation operations [34,35]. Such air contamination is less likely, and if it happens, can cause respiratory and surgical site wound infections in susceptible patients [27].

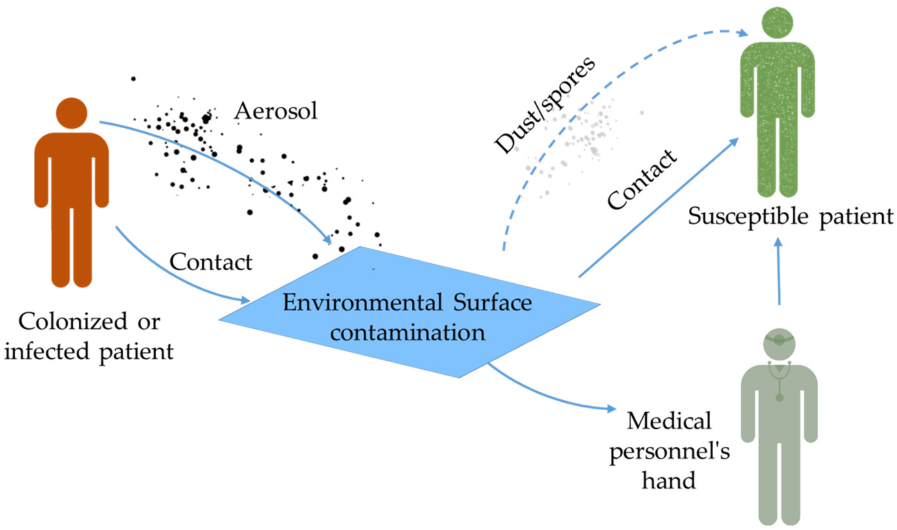

Figure 2. Role of environmental surfaces in the transmission of healthcare-associated infections.

Table 1. Survival of the most common nosocomial pathogens on different substrate conditions.

Microorganisms	Survival Time	
	Various Substrates	Wood
Acinetobacter baumannii	3 days to 1 year (in vitro); 36 days within biofilm and <15 days for non-biofilm-forming strains [31]; <2 days plastic; <7 days aluminum and steel [12]	<24 h [12]
Aspergillus spp.	>30 days [31]	>28 days [36,37]
Candida spp.	>30 days [31]	>30 days
Clostridioides (*Clostridium*) *difficile*	5 months for spores; 15 min (dry surface) and 6 h (moist surface) for vegetative form [31]	N/A
Coronavirus SARS CoV 1 and 2	<5 min up to 24 h (on paper), 5–28 days (at room temp.), 28 days (at 4 °C)	≤24 h SARS-Cov-2 [38,39] 8 to ≤96 h SARS-Cov-1 [40]
Enterococcus spp.	5 days to 30 months [31]	>7 days (flood water) [41]
Escherichia coli	1.5 h to 16 months [31]	1h (food contact) [42], >7 days (flood water) [41], 28 days (farm surface) [43]
Influenza virus	1–28 days (strain dependent), 1–3 days (on banknotes), up to 8 days (admixed in mucous) [31]	1–2 days [44–46], 1–28 days (depending upon environmental conditions) [47]
Klebsiella spp.	>2 h to 30 months; 7 days in detergent solution [31]; > 15 days on plastic, steel and aluminum [12]	<2 days on untreated oak wood [12]
Pseudomonas aeruginosa	6 h up to 16 months (5 weeks on dry floor and few hours in aerosol) [31]	N/A
Shigella dysenteriae	2 h on plastic, aluminum and glass	3 h [28]
Staphylococcus aureus	7 days up to 1 year (in vitro) [31], >15 days (plastic, steel, aluminum) [12], 6 h (copper), 28 days (dry mops) and 14 days (in water) [31]	>28 days on hardwood floor [36] <7 days on untreated oak wood [12]

N/A = no data found.

4. Hygienic and Antimicrobial Behavior of Wooden Surfaces

In the outdoor and humid environment, many microbes are present on wood material. This flora is normally found in soil and on plants [48] and they are responsible for the degradation of organic materials [49]. This is the reason that the indoor air of the wood processing industry can have a higher microbial load as compared to outside air [50]. Therefore, the organic, porous, and moisture-absorbing nature of wood is perceived as microbe heaven. However, in the low moisture and indoor environments, the survival of microbes on wood material is difficult [9]. Moreover, the persistence of hygienically important bacteria and fungi is also low because of the antimicrobial activity of wood material [51]. The theory behind the antimicrobial behavior is linked to the chemical composition and porous hygroscopic nature of wood materials [42].

4.1. Biochemical Composition and Antimicrobial Activity

Wood contains non-structural compounds known as extractives. These chemicals protect wood against microbial degradation and many of them have antimicrobial properties, e.g., tannins, phenolic acids, flavonoids, terpenoids, etc. As these compounds have different chemical natures they may have a different mode of action against various microorganisms as shown in Table 2 [9].

Table 2. Antimicrobial actions of wood chemicals against microbes *.

Target	Wood Chemicals
Cell wall and cell membrane	Flavonoids, tannins, aldehydes, phenolic acids, terpenoids, alkaloids, terpenes
Nucleic acid	Flavonoids, aldehydes, alkaloids
Metals metabolism	Tannins
Protein synthesis	Aldehydes, tannins
Energy metabolism	Flavonoids, phenolic acids
Adhesion and Biofilm formation	Phenolic acids, quinones

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Types and quantity of wood extractives may vary among different wood species and parts of trees, therefore the antimicrobial properties also vary among different wood species (Table 3) [52] and extractives from different parts of wood, i.e., sapwood and heartwood [53]. However, there is only a minor difference of types of extractives present in the same parts of different trees of a wood species growing in different regions [54,55]. Likewise, no significant difference in antimicrobial activity was observed among the sessile oak trees collected from different regions in France that had different soil fertilities and, therefore, presumably different growing conditions [56].

Table 3. Grading of wood species depending upon the hygienic suitability *.

Bacteria	Ranking	Reference
S. aureus, P. aeruginosa, Enterobacter faecium, Bacillus subtilis	Pine > larch	[57]
E. coli	Pine = oak = larch > maple > spruce > beech > polar	[58]
E. faecium	Pine = oak > larch = maple = spruce = beech = poplar	
B. subtilis, P. fluorescens	Oak > spruce	[59]
Poultry manure flora	Pine > larch = maple	[60]
E. coli 0157:H7	White ash > red oak > black cherry > maple	[61]
E. coli, E. faecium	Pine > poplar = beech	[62]
S. aureus, P. aeruginosa, A. baumannii	Oak > Douglas fir = pine > poplar	[63]
S. aureus, E. coli, E. faecalis, Streptococcus pneumoniae	Pine > spruce	[64–66]
E. coli, Pichia membranifaciens, P. aeruginosa, S. aureus	Norway spruce > beech > poplar	[67]

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Various treatment variables can influence the composition of extractives in wood. For example, heat treatments are the part of wood processing, and they are used to increase the durability of this material [68]; meanwhile, heating can accelerate the emissions of volatile organic compounds [64], and as these VOC are also responsible for the antimicrobial activity of wood [69], the antimicrobial behavior may change with heat treatments [56,64].

Logically, some VOC are lost during the usage and storage life of wood, therefore, an influence on the VOC-based antimicrobial activity is expected, however, in our previous study, we observed that the antimicrobial activity of various wood samples stored for two years did not change [52]. Schönwälder et al. [62] also reported that the age and storage time of pinewood did not influence its antimicrobial behavior.

Wood extractives are also used to treat the surfaces of less durable wood to increase their durability against microbial biodegradation [70]. Meanwhile, the removal of extractives has been reported to increase the thermal durability of wood [71]. In such cases, extracting these compounds for surface treatment of wood could give desirable results of durable and antimicrobial wooden surfaces. However, further studies are needed to evaluate the influence of such treatments on indoor VOC emissions.

Wood is an acidic material due to the presence of acidic functional groups in the polymers and extractives of wood. The pH of different wood species ranges from slightly acidic, e.g., pH of poplar and fir is 6, to very acidic, for example, pH of oak wood species can be 3.5 [72]. This acidic environment can pose a challenge to microbial growth when compared to inert solid inanimate surfaces.

4.2. Role of Physical Structure in the Antimicrobial Activity of Wood

The physical structure of wood contributes as a microbial counter mechanism mainly by moisture regulation. The porosity and hygroscopic properties of wood are the main characteristics involved in this behavior; however, controversies surround the microbial survival and hindrance in cleaning due to these physical properties.

4.2.1. Porosity of Wood

Wood is a product of a living tree, therefore it contains the dead elongated cells and they appear in the form of pores at the surface. The porosity varies with the anatomy of wood species, part of tree, and cutting plane of wood. It is sometimes perceived that the open pores of untreated wood surfaces could contain the microbes, ultimately making surface cleaning and microbial removal difficult. Microbes can for sure enter into the porous surfaces of wood, however, they should not necessarily be considered as a hygienic risk. Many studies have shown that the porosity of wood can be a challenge to recover microbes from wood and it can influence the interpretation of microbial survival results. In a previous review, we reported that the recovery of microbes was dependent upon the method of recovery and the moisture content of samples, however, the best results were obtained when the elution-based methods were used [51]. Using the elution-based recovery method to study the microbial survival, we observed that microbial recovery from wood and non-porous materials was similar, however, the survival of most common HAI bacteria was lowest on wood compared to other surfaces such as plastic, steel, or aluminum [12]. In a similar study, Vainio-Kaila et al. [73] observed that lower CFU of *E. coli* and *L. monocytogenes* were recovered from pine heartwood as compared to a glass surface. To further test whether the cultivable bacetria were still hiding in pores or not, they resuspended the wood pieces in the culture medium to let the hidden microbes grow. After one day of incubation, no microbial growth was observed, proving that no culturable microbes were hidden inside the pores [73].

The porosity of wood does not necessarily impact its cleaning, for example, studies of wooden cutting boards have shown that the in-use methods of cleaning were equally efficient for wood as they were for plastic surfaces [59,74–79]. In addition, washing does not decrease the cleanability of wood over time [80] and the action of disinfectants in cleaning equally efficient for cleaning *E. coli, L. monocytogenes, P. aeruginosa, S. aureus, C. jejuni, Salmonella* Typhimurium, *E. coli* O157:H7 on both the plastic and wooden boards [81–84]. Another recent study from indoor hospital surfaces showed the wipe cleaning with disinfectant was sufficient to decrease the microbial numbers on wooden surfaces [8].

Porous surfaces have a greater surface area as compared to non-porous surfaces and it may help in faster drying. Therefore, wood dries faster as compared to non-porous materials [85]. A study by Chiu et al. [86] observed that *Vibrio parahaemolyticus* survived less on porous material (bamboo and wood) as compared to smooth surfaces (plastic, stainless steel, and glazed ceramic), and this difference in survival is more likely because the smooth surfaces retain surface moisture for a longer time [87].

As described above, the pores are the long cells of wood and they can have a length of 3 mm, likewise, the microbes can descend deep inside the pores on wood. However, most porosity is on transversally cut (RT) wood, which is not commonly used for construction operations [12]. Prechter et al. [88] reported that *E. coli* cells and spores of *Bacillus subtilis* descended deeper (around 3 mm) in RT cuttings than in longitudinal cut (LT) wooden boards. In contrast, boards with LT faces are easier to clean because of shallow and wider openings on the surface [89]. The persistence of porosity of wooden surfaces may change over time, for example, Kotradyova et al. [8] reported that the pores of wooden surfaces were filled with organic debris and dust during the usage life of wooden surfaces inside the hospital buildings. However, it still remains to be investigated, how long it takes for the filling of pores in various indoor environments and how it can influence the surface hygiene.

Overall, the transfer of microbes from wooden surfaces to food or hands is also lower as compared to non-porous surfaces [90–93]. For example, a recent study reported that *E. coli* and *Penicillium expansum* not only survived less on wood compared to plastic and cardboards but their transfer from wood surface to apples was also lower [42]. However, if the microbes survive inside the surfaces, they are a continuous risk, in this scenario, innovative microscopic tools can be handy for risk assessment and microbial bio-distribution studies [77,89].

4.2.2. Hygroscopicity and Capillary Action

Hygroscopicity of a material is the property of absorbing and adsorbing moisture from the environment. This ability is influenced by environmental humidity and temperature, and free water, bound water, and fiber saturation point of the wood [94]. Most bacteria and some fungi are sensitive to desiccation and need a water potential of ≤ -2.8 MPa for growth, motility, and nutrient uptake [9,58]. However, properly dried wood (12% moisture) has a higher water potential that does not offer enough water for microbial growth and multiplication [9,58]. This is the reason that the hygroscopic nature of wood leads to faster absorption of moisture as compared to other non-porous contact surfaces, consequently, microbes survive least on wood compared to non-absorptive smooth surfaces such as plastics and metals [12,86,95–97]. However, after reaching the fiber saturation point, wood does not adsorb more moisture and the hygroscopic antimicrobial activity may diminish. For example, Gehrig et al. [85] reported very high *E. coli* counts on both polyethylene and wood, while the bacterial number was lower on wood in a drier environment.

Coating of wood materials may decrease or diminish the surface hygroscopicity, thus influencing microbial adhesion and survival [67]. Hedge [16] studied the survival of *E. coli*, *P. aeruginosa*, *S. aureus* on untreated and varnished beechwood, and plastic. The microbes decreased fastest on natural wood, followed by varnished wood and plastic. Here, the difference of survival can be attributed to the moisture absorbing ability of surfaces, especially the difference between varnished and no-varnished wood.

The lower microbial recovery and moisture retention of wooden surfaces also lead to the assumption that the microbes are strongly attached to wooden surfaces which could help the biofilm formation [98]. However, many studies have shown that microbial attachment to wood is not stronger compared to other smooth surfaces [67]. In fact, in our recent study, we found that the bacteria attached more to non-porous melamine surfaces and formed biofilm while no biofilm was found on oak wood surfaces in similar experimental conditions [99].

5. Conclusions and Future Outlook

Wood material is used in the green healthcare buildings, mostly as a medium to non- contact surfaces. Therefore, it very unlikely that wooden surfaces would increase HAI transmission.

Many wood species have antimicrobial properties due their chemical nature and physical structure. In addition, various microbes responsible for HAI survive less on wooden surfaces compared to other porous or non-porous surfaces. However, future studies should investigate whether the use of wooden surfaces inside the healthcare buildings can influence the prevalence and transmission of HAI.

Porosity of wood material can offer some hindrance in cleaning, however, with proper cleaning methods the cleanability of wooden and non-wooden surfaces is similar. Meanwhile, there is no evidence that the microbes would hide inside the pores of wood and become a risk of transmission after cleaning. In addition, the filling of wooden pores with debris and dust in the indoor healthcare environment also needs exploration to see if it can influence the microbial survival or cleanability of surfaces.

As the antimicrobial properties of wood materials are influenced by various factors, future studies should consider the variables of the species, treatment, cutting, and age of wood while studying the hygienic properties of this material.

There are no current estimates on the amount and economy of wood usage in the healthcare buildings. Therefore, respective stakeholders should investigate these figures to estimate the real value addition of wood usage in the healthcare buildings to the economy.

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