

Coupling Cu-MOF and Flexible Wood as Active Antimicrobial Membrane

Manish Neupane, Zhenyu Shen, Xiahua Zhong, Qiangyu Yan, Dale K. Hensley, Katelynn Marquez, Jinwu Wang, Zhiyong Cai,* and Yingchao Yang*



Cite This: *ACS Appl. Bio Mater.* 2025, 8, 11125–11133



Read Online

ACCESS |



Metrics & More



Article Recommendations

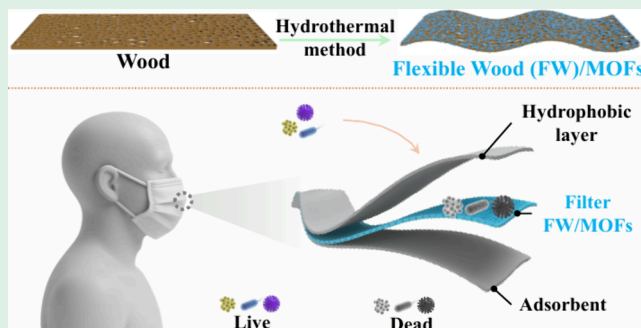


Supporting Information

ABSTRACT: Airborne microbes such as bacteria, viruses, or fungi are a major cause of respiratory ailments, including allergies and pathogenic infections. Despite advances in modern healthcare and public health measures, preventing the transmission of airborne microbes is still very challenging. The microbes may stay alive for a while after landing on a face mask, giving them the chance to infect another individual. In face masks, the laminated materials are primarily made of nonrenewable polystyrene, polyethylene, polycarbonate, or polyester fibers and are even coated with polytetrafluoroethylene for high-efficiency ones. A holistic approach is to disinfect the microbes on face mask before inhaling into the upper respiratory tract with functionalized green materials. In this work, fast-growing balsa wood (BW) sheets were first converted into flexible membrane, followed by in situ growth of Cu-based metal–organic framework (Cu-MOF) into pores. The membrane maintains great flexibility, as demonstrated through mechanical folding and twisting. The agar diffusion test was used to qualitatively assess the efficacy of a flexible membrane coupled with MOF particles in antimicrobial application against Gram-positive and Gram-negative bacteria causing respiratory illness. The inhibition zones with a radius of ~ 2 mm were observed against *Klebsiella pneumoniae* and *Pseudomonas aeruginosa*, while a larger inhibition zone with a radius of ~ 4 mm was recorded against *Staphylococcus aureus*, indicating great potential in inhibiting the production of all strains of microbes. Such green functional materials would find a broad bio application to benefit human health.

In this work, fast-growing balsa wood (BW) sheets were first converted into flexible membrane, followed by in situ growth of Cu-based metal–organic framework (Cu-MOF) into pores. The membrane maintains great flexibility, as demonstrated through mechanical folding and twisting. The agar diffusion test was used to qualitatively assess the efficacy of a flexible membrane coupled with MOF particles in antimicrobial application against Gram-positive and Gram-negative bacteria causing respiratory illness. The inhibition zones with a radius of ~ 2 mm were observed against *Klebsiella pneumoniae* and *Pseudomonas aeruginosa*, while a larger inhibition zone with a radius of ~ 4 mm was recorded against *Staphylococcus aureus*, indicating great potential in inhibiting the production of all strains of microbes. Such green functional materials would find a broad bio application to benefit human health.

KEYWORDS: MOF-199, balsa, flexible wood, microbes, filter



1. INTRODUCTION

Airborne microbes, such as bacteria, viruses, or fungi, represent a major class of biological contaminants, spreading from one individual to another through the air. Airborne microbes are a leading cause of respiratory ailments, including allergies and pathogenic infections.^{1,2} Despite significant progress in healthcare and public health interventions, preventing the transmission of airborne pathogens is still very challenging. One of the major reasons is that aerosols with a typical size of $2\text{--}3\ \mu\text{m}$ and originating from exhaled respiratory droplets can remain airborne for a period due to their low settling velocity.^{3–5} Consequently, another individual could inhale and get infected. Viruses may remain viable on vinyl wall coverings for up to 48 h. Surprisingly, the viruses are active on paper cardboard and stainless steel even after 72 h.^{6–8} In addition to direct transmission, indirect transmission through a contaminated inanimate surface is also a key route. To date, widespread infections have still been reported across the globe. The total seasonal influenza deaths and infections are estimated to be around $\sim 290\text{--}650$ thousands and $\sim 3\text{--}5$ million, respectively.^{9–11} Without a doubt, communicable

respiratory diseases impose huge strains on global health systems and economies every year.

Preventive measures including hand hygiene and face mask use remain essential strategies to limit the spread of respiratory infections such as influenza, respiratory syncytial virus (RSV), and other viral pathogens. Face mask wear can block or filter airborne virus-carrying particles through the working of colloid and interface science. For example, the “Not Oil Resistant 95” (N95) face mask is effective at filtering 95% of airborne particles with size larger than $0.3\ \mu\text{m}$.^{12,13} Most disposal face masks, by comparison, are designed to filter particulate matter down to PM 2.5 or smaller.^{13,14} However, respiratory microbes are primarily transmitted through droplets and aerosols, which are colloidal particles expelled during breathing, talking, or coughing. These particles typically range from 0.1 to several

Received: September 16, 2025

Revised: November 5, 2025

Accepted: November 5, 2025

Published: November 11, 2025



micrometers and can be readily inhaled.^{5,15} Consequently, complete prevention of their transmission remains difficult, even with the use of N95 masks. To address this limitation, efforts have been focused on integrating functionalization agents into face masks to enhance their protective and antimicrobial performance.^{7,16–19} The incorporation of antimicrobial and self-disinfecting agents, such as metal and metal oxide nanoparticles (e.g., CuO, ZnO, and Ag) as well as photosensitizers capable of generating reactive oxygen species (ROS), has been explored to functionalize face masks and inactivate microorganisms within a short time.^{17,19–22} Other strategies involve self-cleaning capability through the use of superhydrophobic materials, such as graphene, or incorporating triboelectric nanogenerators within mask layers to stabilize electrostatic charges and prolong filtration performance.^{19,23–27} Among metal/metal oxides, copper has been recognized for its antimicrobial efficacy for centuries.^{28,29} Copper metal surfaces and nanoparticles have demonstrated inhibition against pathogenic bacteria such as *Escherichia coli* and *Staphylococcus aureus* through mechanisms including ion release, ROS generation, and membrane disruption.^{28,30–33} Similarly, cupric oxide (CuO) nanoparticles incorporated into polyacrylonitrile (PAN) nanofibers via electrospinning have shown pronounced antibacterial activity against *E. coli* and *Bacillus subtilis*, highlighting the potential of copper-based additives in functionalized filtration media.²⁰ In addition, hybrid materials such as copper-zeolitic imidazolate frameworks (Cu-ZIFs) have exhibited potent antimicrobial effects against *E. coli* and *Streptococcus mutans*.²¹

The filter material in face masks is primarily made of nonrenewable materials, such as glass fibers, polyester fibers, metallic wools, etc. To advance green technology, the sustainable and low-cost renewable forest resources such as wood and woody biomass can serve as valuable raw materials.^{34,35} Cu-based metal organic framework (Cu-MOF, also known as MOF-199, HKUST-1 or CuBTC), which has been synthesized into bamboo and balsa wood (BW), exhibited antimicrobial property with minimizing the *S. aureus* colony level to 2.08 (colony-forming unit) from 8.98 CFU cm⁻².³⁶ However, these materials are typically quite brittle and are unable to be directly integrated into face masks. Recent research demonstrated that wood, taking BW as an example, can be chemically treated to create a super flexible, biocompatible, and porous structure that could be used for water purification, flexible electronics, and three-dimensional bio scaffolds.^{34,37–39} The engineered flexible wood offers an excellent scaffold for the in situ growth of MOF-199, enabling the development of functionalized, sustainable filter media. Therefore, growing MOF-199 into flexible wood could serve as a sustainable alternative to conventional mask filter layers, offering a combination of structural filtration and an intrinsic antimicrobial functionality. In this work, a hybrid structure was fabricated by coupling the flexible BW (FBW) with in situ grown MOF-199, which not only has great flexibility, but also holds a promising antibacterial potential. MOF-199 was hydrothermally grown within the pores down to a few micrometers from the surface of flexible wood sheets. The agar diffusion test was used to qualitatively assess the efficacy of a flexible membrane coupled with MOF-199 particles in antimicrobial application against Gram-positive and Gram-negative bacteria causing respiratory illness. The new materials developed in this work would expand the use of wood materials, provide effective and affordable air filtration

materials, and address the demands of future airborne disease outbreaks.

2. EXPERIMENTAL SECTION

2.1. Chemicals. The chemicals in this work were used as received, without further purification. The chemicals include sodium hydroxide (NaOH, >97%, Sigma-Aldrich), sodium sulfite (Na₂SO₃, >98%, Sigma-Aldrich), copper nitrate trihydrate (Cu(NO₃)₂·3H₂O, 99% for analysis, Fisher Chemical), 1,3,5-benzenetricarboxylic acid (H₃BTC, >98.0%(T), Tokyo Chemical Industry), *N,N*-dimethylformamide (DMF, certified ACS, Fisher Chemical), and ethanol (Fisher Chemical).

2.2. Fabrication of FBW. BW was used for the fabrication of the flexible wood. NaOH, Na₂SO₃, and deionized (DI) water were used for processing the wood. To convert BW into flexible wood, 50 mL of DI water, 5.07 g of NaOH, and 5.144 g of Na₂SO₃ were mixed and added into a Teflon-lined stainless-steel autoclave of 100 mL capacity along with radially cut 2.5 × 2.5 × 0.2 cm BW sheets. The autoclave was sealed and heated to 120 °C in a furnace for 5 h. The autoclave was removed and cooled down under tap water for 15 min. Subsequently, the slices of BW were taken out, placed in 20 mL DI water, and washed in an ultrasonic cleanser for 15 min. Finally, the sheets were kept in air for natural drying.

2.3. Growth of MOF-199 into FBW Sheets. The FBW sheets obtained prior were used for in situ growth of MOF-199 following the procedure described in our previous work.⁴⁰ 22.5 mL ethanol and 1.5 g of H₃BTC were mixed to form a uniform solution. Separately, another solution was made with 22.5 mL of DI water and 3.114 g of Cu(NO₃)₂·3H₂O. The two solutions were then mixed and stirred for 10 min. The FBW sheets were soaked in the solution and together sealed into a Teflon-lined autoclave. The autoclave was heated at 100 °C for 10 h for MOF-199 growth. The autoclave was taken out and set aside to cool naturally to room temperature. The FBW with MOFs was ultrasonicated in 20 mL of DI water for 25 min until the washing liquid became clear, ensuring the removal of any loose particles, and dried in air. The flexible wood obtained with MOF-199 was abbreviated as FBW-MOF. For antimicrobial and breathability tests, the thickness of FBW-MOF was maintained at 1.25 mm.

2.4. Three-Point Bending Tests. Three-point bending tests were performed by Deben Micro Tensile Tester 200 with a 200 N load cell on untreated BW, FBW, FBW with 10 min of streaming at room temperature, and FBW with 5 min of breath at room temperature. The force resolution of the load cell was 0.001 N. The displacement rate was set as 0.2 mm min⁻¹. After the bending tests, the elastic modulus was calculated and compared.

2.5. Material Characterization. Morphology and composition of FBW with MOFs were characterized by scanning electron microscopy (SEM, Quanta 600 with EDS). The crystallinity was identified with a Rigaku Ultima IV X-ray diffractometer (XRD) with Cu K α as the X-ray source.

2.6. Antimicrobial Test. BW, FBW, and MOF-199 pellets and FBW-MOF were prepared for agar testing. *Pseudomonas aeruginosa*, *Klebsiella pneumoniae*, and *S. aureus* were streaked onto Luria-Bertani (LB) agar plates and incubated overnight to ensure viability and purity. Single colonies from the agar plates were suspended in sterile water, adjusted to a 0.5 McFarland standard, and then evenly spread on LB agar plates using sterile cotton swabs. For BW, FBW, and FBW-MOF, the materials were cut into 6 mm diameter disks to be placed on the agar plates. Since MOF-199 was obtained in powder form, it was compacted into pellets by placing a fixed volume of the powder in a 6 mm diameter die and pressing it with a hydraulic press. After drying, these disks were placed on the agar, and plates were incubated at 35 °C for 16–24 h. Inhibition zones appeared as clear circular areas around the disks, where bacterial growth was suppressed. Zone radii were measured in millimeters from the edge of the disk to the edge of the clear zone. Larger radii indicated stronger antibacterial activity, while smaller or absent zones indicated weaker or no antibacterial activity.

3. RESULTS AND DISCUSSION

For any respiratory diseases, a couple of precautions are highly recommended to prevent and slow down transmission of virus and bacteria, including (1) avoid being around people who are more likely to get sick; (2) wear a high-quality mask when around others in public; and (3) use hand sanitizer to kill microbes on hands. The first two strategies can be regarded as passive defense, while the last approach is active defense. In the passive defense strategy through a face mask, microbial pathogens are not directly deactivated. When microbes contact face masks, penetration through the material is physically blocked to some extent, thereby providing protection against microbial ingress. However, microbes can remain viable on the surface of face masks for a period, posing a risk of indirect transmission to other individuals upon contact schematically shown in Figure 1 passive defense. If microbes landing on a

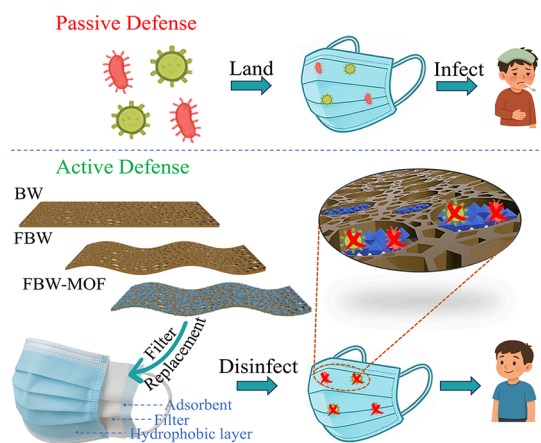


Figure 1. Schematic of passive and active strategies to prevent microbe transmission.

face mask could be killed directly, the face mask will function as the first line in both passive and active defense, minimize the transmission of microbes, and further prevent infection to individuals around. Shown in Figure 1 active defense, the filter layer in face masks is targeted to be replaced with FBW-MOF, in which Cu-MOFs are embedded into pores of FBW are active ingredients to disinfect microbes. The newly conceptualized face masks would offer active defense and prevent secondary infections.

3.1. Morphology of In Situ Grown MOF-199 in FBW.

Toward replacing the filter layer within face masks, the main material should be porous and flexible. The lightweight (150 kg m^{-3}) and fast growth (12 ft. after germination within 6 months) make BW stand out of all other wood in fabrication of highly porous framework.^{41,42} The BW was sliced into sheets with a thickness of approximately 2 mm along the radial direction of growth. To preserve the native porous architecture and prevent pore collapse during sample preparation, the wood was carefully polished after cutting, which ensured efficient and uniform flow of chemical precursors during subsequent treatment and MOF-199 growth.

Figure 2a–c displays SEM images of the porous structure of BW along radial and longitudinal directions. In Figure 2a, the surface of the BW is clean and devoid of any debris or obstructions that might block the channels. This pristine surface condition is essential as it maximizes the contact area between the wood substrate and chemical precursors,

facilitating thorough infiltration and reaction throughout the material. Figure 2b highlights the presence of numerous small pores lining the interior channels of the wood. These micropores serve as conduits for the transport of chemical precursors into the wood's structure, enhancing precursor diffusion and penetration. The interconnected pore network ensures that chemicals can reach internal surfaces effectively, promoting uniform delignification and post MOF-199 growth. The channels themselves vary in size, ranging approximately from 12 to 44 μm in diameter, providing a hierarchical porous structure for MOF-199 growth (shown in Figure 2c). Through a simple one-step delignification process, the BW was converted into FBW. Figure 2d displays a SEM image of the FBW surface, which exhibits a markedly delaminated morphology compared to the pristine BW. This structural change can be attributed to the removal of lignin, a natural polymer that functions as an adhesive binding cellulose and hemicellulose within the wood cell walls, and partial removal of hemicellulose. Sodium sulfite reacts with lignin to form water-soluble compound whereas partial hemicellulose removal is achieved by hydrolysis in the presence of sodium hydroxide.⁴³ Once lignin and hemicellulose (partially) are removed, the bonding between these structural components is weakened, resulting in more delaminated walls. Figure 2e,f shows these structural changes along the longitudinal direction. The channels are well preserved and remain intact despite the delignification process. The retention of the channel architecture is particularly advantageous, as it provides an ideal framework for uniform and efficient growth of MOF-199 growth. Additionally, Figure 2f shows a porous cross-channel, a structural feature characteristic of BW. Such cross-linking pathways can significantly facilitate multidirectional fluid flow, thereby improving precursor infiltration and proper delignification. In addition, these porous cross-channels can serve as extra filtration layers, intercepting pollutants or microorganisms that might bypass the longitudinal channels. Figure 2g–i illustrates the in situ growth of MOF-199 within FBW. As shown in Figure 2g, MOF-199 is grown uniformly across the wood surface, creating a continuous layer and establishing an effective antimicrobial barrier, ensuring that microbes encounter active MOF-199 surfaces throughout. The inset in Figure 2g shows the octahedral crystal structure of the MOF-199. The hierarchical channel of BW (shown in Figure 2f) dictates the growth pattern of the MOF-199. Larger channels are almost entirely filled with MOF-199, providing a robust physical and chemical defense while maintaining open pathways in adjacent smaller channels to ensure adequate airflow. Such configuration would help prevent excessive blockage of the porous structure, thereby balancing protective capability with breathability. Smaller channels, on the other hand, are partially filled with MOFs to a depth of approximately 60–100 μm from the surface, as seen in Figure 2i. The partial filling is beneficial, as it creates an antimicrobial zone near the surface while leaving the rest of the channels unobstructed. The obtained multifunctional porous architecture would effectively hinder microbial penetration while preserving the necessary air permeability. Figure 2j shows the elemental analysis of individual MOF-199 particles, revealing the presence of copper and oxygen. As MOF-199 particles were loaded onto an aluminum SEM stub, small aluminum peak was also detected. Moreover, XRD analyses in Figure 2k,l further confirm the growth of MOF-199 in FBW as the MOF-199 peaks were prominent in FBW-MOF.

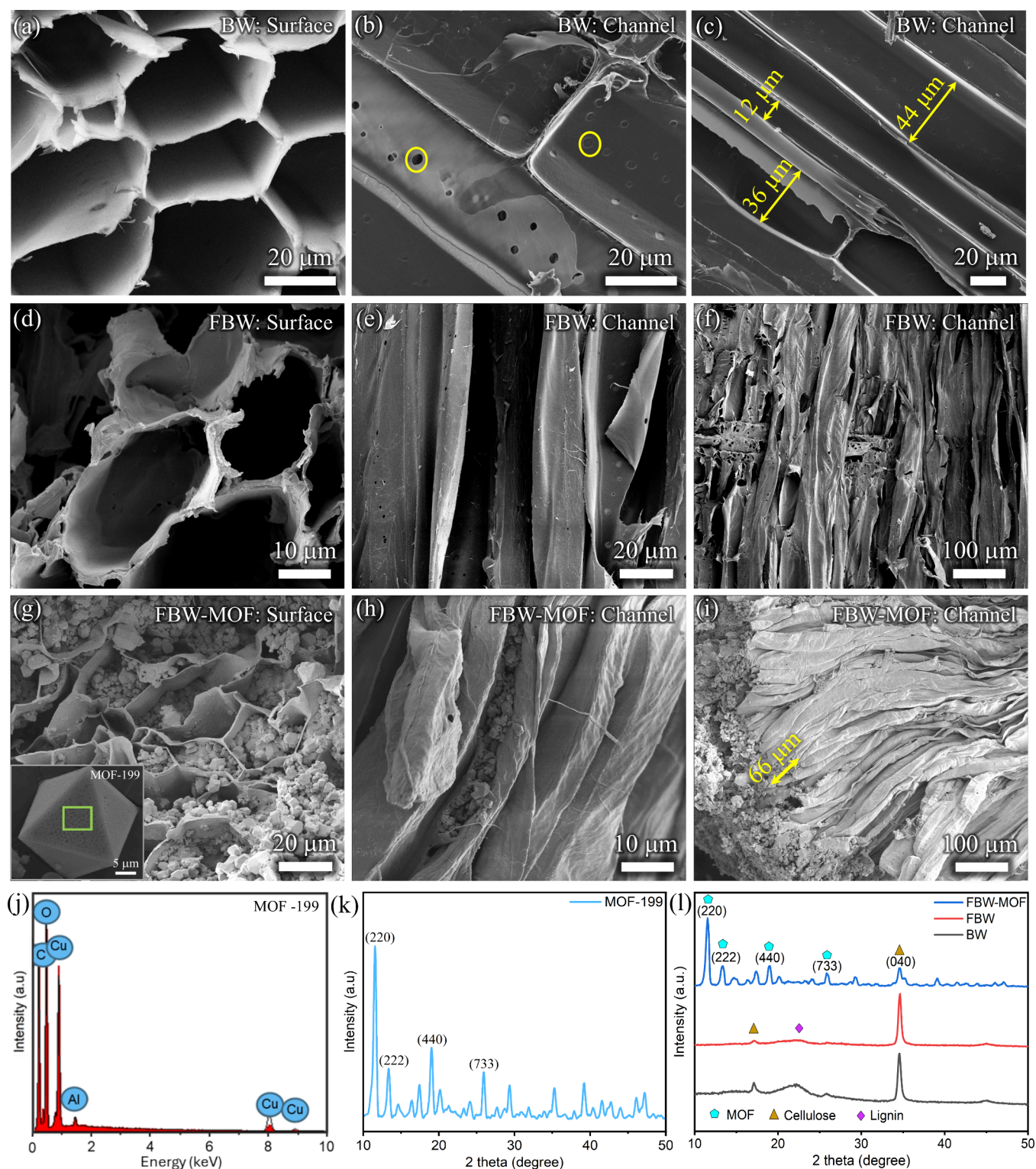


Figure 2. Morphology and characterization of BW, FBW, and FBW-MOF. SEM images of (a–c) BW: (a) surface and (b, c) channels. (d–f) FBW: (d) surface and (e, f) channels. (g–i) FBW-MOF: (g) surface (inset: MOF-199 particle) and (h) and (i) channels. (j) EDS of MOF-199. (k) XRD of MOF-199. (l) XRD of BW, FBW, and FBW-MOF.

3.2. Mechanical Properties. To evaluate the mechanical behavior of FBW and FBW-MOF, their degree of deformation was compared with that of pristine BW as shown in Figure 3a–i. Pristine BW, owing to its lignin-rich structure, exhibits only limited flexibility. As shown in Figure 3a, it can be bent slightly before fracture, reaching a maximum curvature (κ) of

approximately $1/0.69 \text{ m}^{-1}$, highlighting the inherent brittleness of untreated wood. In contrast, the FBW demonstrates a markedly enhanced bending capability. As demonstrated in Figure 3b, FBW achieves a curvature of $1/0.12 \text{ m}^{-1}$, over five times greater than that of pristine BW, without sustaining damage. This improvement can be attributed to the

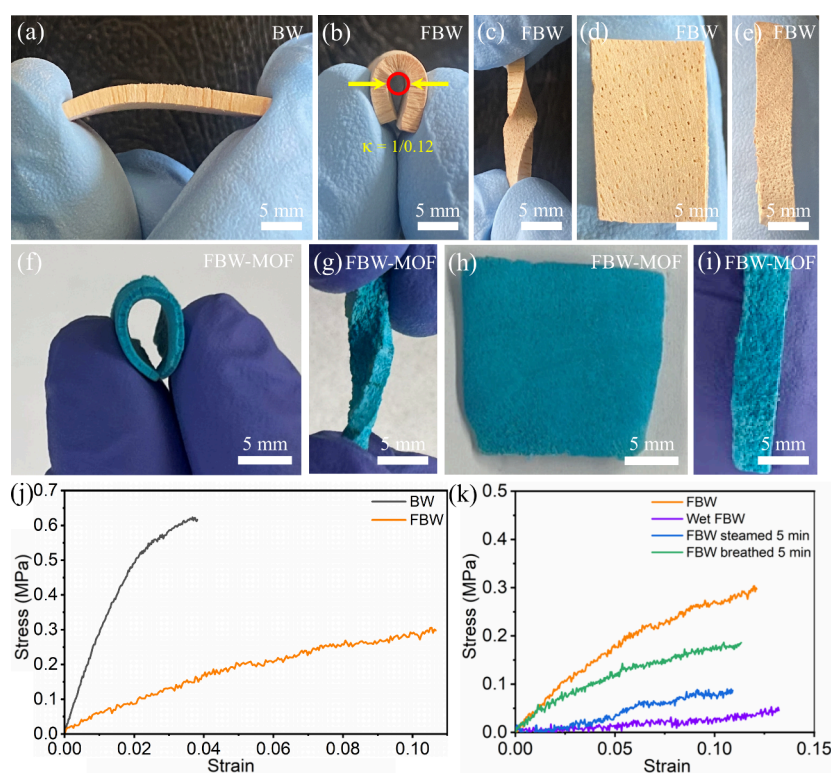


Figure 3. Mechanical behaviors of BW and FBW with a thickness of 2 mm. (a) Buckling of pristine BW. (b) Folded BW. (c) Twisted FBW. (d) and (e) Restored FBW after folding and twisting. (f) Folded FBW-MOF. (g) Twisted FBW-MOF. (h) and (i) Restored FBW-MOF. (j) Stress–strain curves of pristine BW and FBW. (k) Stress–strain curves of dry, wet, steamed, and breathed FBW.

Table 1. Mechanical Properties of Pristine and FBW

sample	span length (mm)	width (mm)	thickness (mm)	initial linear slope (N/m)	flexural modulus (MPa)	averaged flexural modulus (MPa)
pristine BW	23	5.25	2.79	0.56	14.88	19.14 ± 8.52
dry FBW	23	6.09	2.47	0.13	4.22	4.39 ± 0.59
wet FBW	23	6.79	2.85	0.02	0.45	0.40 ± 0.14
5 min steamed FBW	23	5.28	2.47	0.11	4.22	2.56 ± 1.21
5 min breathed FBW	23	5.72	2.54	0.12	3.77	3.81 ± 0.34

delignification process, which reduces interfiber bonding and increases interfacial slippage between cellulose microfibrils, thereby imparting greater flexibility. Furthermore, FBW can be easily twisted, as shown in Figure 3c, while the pristine BW is almost unable to be twisted. Figure 3d,e reveals excellent shape recovery of FBW. After substantial bending and twisting, the deformed FBW returns to its original shape without visible cracks or permanent deformation. Such elastic recovery is indicative of great mechanical stability and robustness, even with significant mechanical strain. Similar behavior is observed in the FBW-MOF shown in Figure 3f–i. Despite MOF-199 particles, FBW-MOF retains high flexibility, allowing it to bend and twist easily without compromising the structure. Moreover, FBW-MOF also demonstrates complete shape recovery after deformation, suggesting its robustness toward practical applications. The combination of flexibility and mechanical stability makes FBW-MOF meet the prerequisites toward replacing traditional filter materials in masks.

To quantify the flexibility of the BW and FBW, three-point bending tests were performed. In the case of any size effect on flexibility, all specimens were largely trimmed into similar width and thickness. The displacement rate was set as 0.2 mm min^{−1}. Figure 3j shows the stress–strain curves of BW and

FBW. The flexural elastic modulus can be calculated using classical mechanics of materials (eqs 1 and 2) as follows:

$$E_{\text{flex}} = \frac{L^3 F}{48 I \delta} \quad (1)$$

$$I = \frac{wh^3}{12} \quad (2)$$

where L , w , and h are the span length, width, and height, respectively, of the tested wood specimen, E_{flex} is flexural modulus, F is the applied load, I is the moment of inertial, and δ is the deflection of the tested specimen.⁴⁴ The flexural modulus of pristine BW averaged from five specimens is 19.14 ± 8.52 MPa as presented in Table 1. Such measurement is in good agreement with the reported modulus of rupture via static bending. After hydrothermal treatment, the FBW was dried in a drying oven. The average flexural modulus of the dry FBW is 4.39 ± 0.59 MPa, which is less than one-fifth of that of pristine BW. The improved flexibility originates from (1) multichanneled 3D porous structure is well preserved after chemical treatment; (2) the amount of lignin and hemicellulose decreases; (3) open latticed hexagonal cell lumina are delaminated.

When the FBW is laminated into a face mask, the breath containing water molecules will inevitably increase the humidity, which could affect the flexibility of the FBW. To have a clear understanding of humidity effect, the specimens were treated in three different conditions followed by three-point bending, including FBW after taking out water and held until no water dripping, dry FBW was steamed for 5 min using a humidifier at room temperature, and dry FBW was breathed for 5 min by a volunteer student to mimic the real application environment. Averaged from five specimens, the flexural modulus of wet FBW is only 0.40 ± 0.14 , suggesting superior flexibility compared with pristine and dried FBW. The improved flexibility originates from the hydrogen bonding between the hydroxyl groups on nanocellulose and water molecules. Generally, hydrophilic nanocellulose in wood has many hydroxyl groups. Under mechanical deformation, the breaking and rebonding of hydrogen bonds will enable the interface sliding among nanocellulose as well as between nanocellulose and the added water molecules. In contrast to getting wet directly, the dry FBW was steamed. The calculated flexural modulus is 2.56 ± 1.21 MPa, which is not surprising to fall between the flexural moduli of dry and wet FBW, as the water content in the steamed FBW is higher than that in dry FBW, but lower than that in wet FBW. To continue decreasing the water content and mimic the humidity in a face mask in use, the dried FBW was breathed for 5 min. The average flexural modulus is 3.81 ± 0.34 MPa. Such measurement indicates that if the FBW is laminated into a face, the flexibility can be well maintained.

3.3. Antimicrobial Performance. The antimicrobial activity of FBW-MOF was evaluated against three representative bacterial species: *P. aeruginosa*, *K. pneumoniae*, and *S. aureus*. These bacteria are commonly associated with respiratory infections. Among them, *P. aeruginosa* and *K. pneumoniae* are Gram-negative, whereas *S. aureus* is a Gram-positive bacterium. The inclusion of both Gram-negative and Gram-positive species ensures a comprehensive assessment of antibacterial activity across different bacterial classes with distinct cell wall structures. Antimicrobial activity was assessed using the agar diffusion method, where the formation of a clear halo, or inhibition zone, surrounding the test material indicates the suppression of bacterial growth. The radius of this inhibition zone serves as a quantitative measure of antibacterial effectiveness with larger zones corresponding to stronger bactericidal activity.

As shown in Figure 4, no inhibition zones were observed around BW and FBW against any of the tested bacterial strains, indicating negligible inherent antimicrobial activity. By contrast, FBW-MOF shows distinct inhibition zones for all bacteria demonstrating its effective antimicrobial properties. Specifically, inhibition zones with a radius of ~ 2 mm were observed against *K. pneumoniae* and *P. aeruginosa*, while a larger inhibition zone of with a radius of ~ 4 mm was recorded against *S. aureus*, demonstrating enhanced efficacy against the Gram-positive strain. The observed inhibition zones were comparable to those obtained using MOF-199 alone in the form of a pellet, confirming that the incorporation of flexible wood did not diminish the antibacterial activity of the MOF-199. Instead, the flexible wood acted as an excellent scaffold, supporting uniform MOF-199 growth and enabling an efficient antibacterial action. This demonstrates that the flexible wood substrate is highly compatible with MOF-199 and further enhances its applicability by providing a mechanically robust

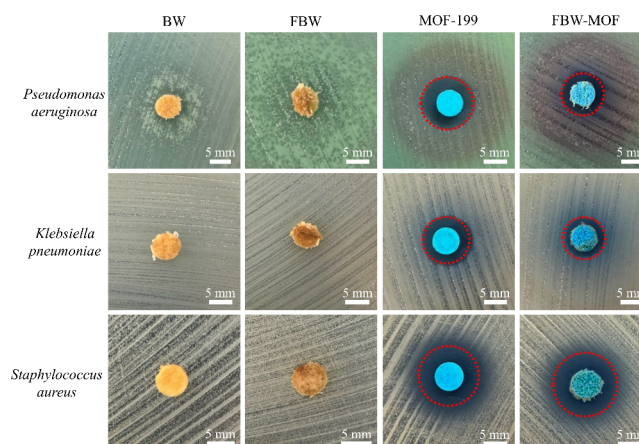


Figure 4. Incubation of *P. aeruginosa*, *K. pneumoniae*, and *S. aureus* with agar diffusion around BW, FBW, MOF-199, and FBW-MOF. The red circles indicate the clear zones of bacterial growth inhibition.

and porous framework to support the antimicrobial functionality. These results highlight the pivotal role of MOF-199 in imparting strong antibacterial properties to the flexible wood substrate and prove the potential of FBW-MOF as a self-disinfecting filter material. The excellent antimicrobial property can be attributed to the release of Cu^{2+} ions from MOF leading to cell membrane disruption, protein denaturation, and oxidative stress through ROS generation.^{28,30–33} The test was repeated three times, consistently yielding similar inhibition zones (Table S1, Supporting Information), thereby demonstrating the reproducibility of the results.

3.4. Breathability Testing. In addition to antimicrobial activity, breathability is a critical requirement for materials intended for use in filtration and protective mask applications. While strong antibacterial performance ensures protection against microbial contamination, adequate air permeability is essential to maintain comfort and usability. Therefore, alongside the inhibition zone studies, the air permeability of the FBW-MOF was systematically evaluated and compared with that of a commercial N95 mask. The experimental setup for such testing is shown in Figure 5. The sample was mounted at the center of the sample holder and positioned between Control A and Control B valves. The measurement procedure was conducted following the sequence: (1) Close Control A and Control B, and then, a vacuum pressure of 6 in.Hg is created by the hand pump. Closing both valves will isolate the

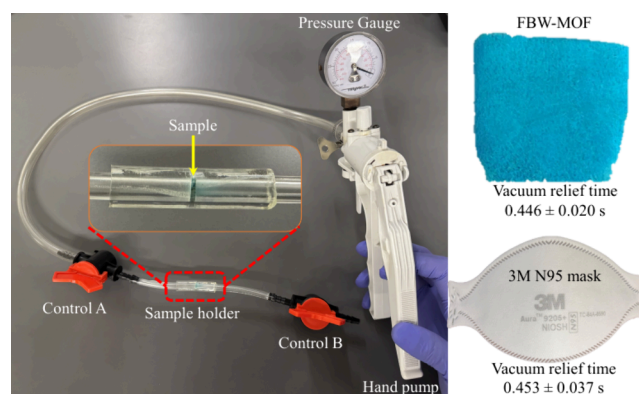


Figure 5. Setup for measuring the breathability along with vacuum relief time comparison between the FBW-MOF and 3 M N95 mask.

sample holder assembly, ensuring that the sample neither influences nor is influenced during vacuum buildup. (2) Open Control A: for this setup, the pressure stabilizes at 5 in.Hg; such stable pressure confirms no leakage occurrence from the sample holder assembly. (3) Open Control B: the time to restore ambient pressure from the vacuum will be recorded. The experiment was repeated three times on one sample with three different samples in total. Individual periods for vacuum relief to ambient pressure are listed in Table S2, Supporting Information.

The FBW-MOF exhibits vacuum relief time (0.446 ± 0.02 s) closely comparable to that of a standard N95 mask (0.453 ± 0.037 s) as listed in Table 2, indicating similar permeability

Table 2. Vacuum Release Time of Different Test Samples

materials	pressure buildup (psi)	relief time (s)
N-95 mask	−5	0.453 ± 0.037
BW	−5	0.496 ± 0.022
FBW	−5	0.601 ± 0.019
FBW-MOF	−5	0.446 ± 0.020

performance. BW shows a vacuum relief time comparable to FBW-MOF whereas FBW exhibited a slightly elevated release time (0.601 ± 0.019 s). The difference between BW and FBW may be attributed to minor collapse of delaminated walls during air extraction to reach the vacuum condition. The subsequent growth of MOF-199 within channels provides additional structural support, thereby mitigating wall collapse and stabilizing the FBW under vacuum condition. These observations suggest that MOF-199 not only imparts antimicrobial properties but also enhances the mechanical integrity of the FBW. Similar testing was performed on the BW cut along the longitudinal direction. The pressure restoration takes a much longer time (1.24 ± 0.032) compared to BW, FBW, and FBW-MOF, which should be due to longitudinally aligned cell walls and the limited presence of cross-channels to facilitate air flow. Therefore, the BW sheets cut from the radial direction to the growth will be ideal for the fabrication of FBW and FBW-MOF with the required permeability. Additionally, to simulate the inhalation process, the hand pump handle was slowly compressed. In the case of the FBW-MOF, no measurable vacuum was generated during this simulation, demonstrating unobstructed airflow through the material.

In addition to the breathability test, whether MOF particles detach from the FBW-MOF was assessed under extreme condition. Details about the assessment can be found in the Figure S1, Supporting Information. Only a minimal number of particles detached and were captured by a double-sided carbon, inferring a quite low likelihood of particle release. The risk of toxicity associated with the use of this material in face masks and biofiltration applications is expected to be negligible.

4. CONCLUSIONS

The chemical treatment of BW helps achieve a flexible, porous, and ecofriendly framework. Mechanical behaviors of the FBW were evaluated under dry, wet, steaming, and breathing conditions to understand if the material has potential to be incorporated into a face mask. The breathed FBW has an average flexural modulus of 3.81 ± 0.34 MPa, indicating that the flexibility is well maintained compared to that of dried FBW. After in situ growth of MOF-199 using a hydrothermal

method, the material stays flexible. With the agar diffusion test, inhibition zones with a radius of ~ 2 mm were observed against *K. pneumoniae* and *P. aeruginosa*, while a larger inhibition zone with a radius of ~ 4 mm was recorded against *S. aureus*, indicating great potential in inhibiting bacterial growth. Given the fact that airborne microbes may stay alive for a while after landing on face mask and further infect another individual, coupling MOFs and flexible wood as effective antimicrobial membrane could become a great structure in preventing the transmission of microbes, aiding in controlling respiratory illness.

■ ASSOCIATED CONTENT

Data Availability Statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsabm.5c01831>.

Measurement of inhibition zones for all samples;
measurement of vacuum relief time for all samples;
and particles detachment test for FBW-MOF (PDF)

■ AUTHOR INFORMATION

Corresponding Authors

Zhiyong Cai — Forest Products Laboratory, U.S. Department of Agriculture, Madison, Wisconsin 53726, United States;
Email: zhiyong.cai@usda.gov

Yingchao Yang — Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, Missouri 65211, United States; orcid.org/0000-0002-0200-3948;
Email: yingchao.yang@missouri.edu

Authors

Manish Neupane — Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, Missouri 65211, United States; orcid.org/0009-0001-9824-7268

Zhenyu Shen — College of Veterinary Medicine, University of Missouri, Columbia, Missouri 65211, United States

Xiahua Zhong — Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, Missouri 65211, United States

Qiangui Yan — Forest Products Laboratory, U.S. Department of Agriculture, Madison, Wisconsin 53726, United States

Dale K. Hensley — Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, United States

Katelynn Marquez — Department of Mechanical and Aerospace Engineering, University of Missouri, Columbia, Missouri 65211, United States

Jinwu Wang — Forest Products Laboratory, U.S. Department of Agriculture, Madison, Wisconsin 53726, United States;
orcid.org/0000-0002-8363-1689

Complete contact information is available at:
<https://pubs.acs.org/doi/10.1021/acsabm.5c01831>

Author Contributions

M.N. and Y.Y. conceived the idea. M.N. and K.M. fabricated flexible wood, grew MOFs, and performed mechanical and permeability testing. Z.S. carried out the agar testing. D.K.H. and X.Z. helped with SEM imaging, XRD, and schematic

drawings. M.N. and Q.Y. analyzed the data and drafted the manuscript supervised by Y.Y., Z.S., J.W., and Z.C.

Funding

The project has been supported by the USDA Forest Service through Grant Nos. 23-JV-11111124-016 and 24-JV-11111124-100.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

Y.Y. thanks to the Center for Nanophase Materials Sciences (CNMS) at Oak Ridge National Laboratory (ORNL) for the characterization support under the user proposal CNMS2023-B-02166. Special thanks are also given to Meghan Boos for the initial screening, Christopher Strehl for setting breathability test, as well as Timothy Ketelboeter and Joseph Destree at USDA Forest Products Laboratory for their help in making this project run successfully.

REFERENCES

- (1) Riley, R. L. Airborne Infection. *American Journal of Medicine* **1974**, *57* (3), 466–475.
- (2) Matricardi, P. M.; Rosmini, F.; Riondino, S.; Fortini, M.; Ferrigno, L.; Rapisetta, M.; Bonini, S. Exposure to Foodborne and Orofecal Microbes versus Airborne Viruses in Relation to Atopy and Allergic Asthma: Epidemiological Study. *BMJ* **2000**, *320* (7232), 412.
- (3) Stilianakis, N. I.; Drossinos, Y. Dynamics of Infectious Disease Transmission by Inhalable Respiratory Droplets. *Journal of Royal Society Interface* **2010**, *7* (50), 1355–1366.
- (4) Liu, L.; Wei, J.; Li, Y.; Ooi, A. Evaporation and Dispersion of Respiratory Droplets from Coughing. *Indoor Air* **2017**, *27* (1), 179–190.
- (5) Duguid, J. P. The Size and the Duration of Air-Carriage of Respiratory Droplets and Droplet-Nuclei. *Epidemiology & Infection* **1946**, *44* (6), 471–479.
- (6) van Doremalen, N.; Bushmaker, T.; Morris, D. H.; Holbrook, M. G.; Gamble, A.; Williamson, B. N.; Tamin, A.; Harcourt, J. L.; Thornburg, N. J.; Gerber, S. I.; Lloyd-Smith, J. O.; de Wit, E.; Munster, V. J. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. *New Engl. J. Med.* **2020**, *382* (16), 1564–1567.
- (7) Seidi, F.; Deng, C.; Zhong, Y.; Liu, Y.; Huang, Y.; Li, C.; Xiao, H. Functionalized Masks: Powerful Materials against COVID-19 and Future Pandemics. *Small* **2021**, *17* (42), 2102453.
- (8) Ronca, S. E.; Sturdivant, R. X.; Barr, K. L.; Harris, D. SARS-CoV-2 Viability on 16 Common Indoor Surface Finish Materials. *HERD: Health Environ. Res. Des. J.* **2021**, *14* (3), 49–64.
- (9) O'Halloran, A. C.; Holstein, R.; Cummings, C.; Daily Kirley, P.; Alden, N. B.; Yousey-Hindes, K.; Anderson, E. J.; Ryan, P.; Kim, S.; Lynfield, R.; McMullen, C.; Bennett, N. M.; Spina, N.; Billing, L. M.; Sutton, M.; Schaffner, W.; Talbot, H. K.; Price, A.; Fry, A. M.; Reed, C.; Garg, S. Rates of Influenza-Associated Hospitalization, Intensive Care Unit Admission, and In-Hospital Death by Race and Ethnicity in the United States From 2009 to 2019. *JAMA Network Open* **2021**, *4* (8), No. e2121880.
- (10) Iuliano, A. D.; Roguski, K. M.; Chang, H. H.; Muscatello, D. J.; Palekar, R.; Tempia, S.; Cohen, C.; Gran, J. M.; Schanzer, D.; Cowling, B. J.; Wu, P.; Kyncl, J.; Ang, L. W.; Park, M.; Redlberger-Fritz, M.; Yu, H.; Espenhain, L.; Krishnan, A.; Emukule, G.; van Asten, L.; Pereira da Silva, S.; Aungkulanon, S.; Buchholz, U.; Widdowson, M.-A.; Bresee, J. S.; Azziz-Baumgartner, E.; Cheng, P.-Y.; Dawood, F.; Foppa, I.; Olsen, S.; Haber, M.; Jeffers, C.; MacIntyre, C. R.; Newall, A. T.; Wood, J. G.; Kundi, M.; Popow-Kraupp, T.; Ahmed, M.; Rahman, M.; Marinho, F.; Sotomayor Proschle, C. V.; Vergara Mallegas, N.; Luzhao, F.; Sa, L.; Barbosa-Ramírez, J.; Sanchez, D. M.; Gomez, L. A.; Vargas, X. B.; Acosta Herrera, aBetsy; Llanés, M. J.; Fischer, T. K.; Krause, T. G.; Mølbak, K.; Nielsen, J.; Trebbien, R.; Bruno, A.; Ojeda, J.; Ramos, H.; an der Heiden, M.; del Carmen Castillo Signor, L.; Serrano, C. E.; Bhardwaj, R.; Chadha, M.; Narayan, V.; Kosen, S.; Bromberg, M.; Glatman-Freedman, A.; Kaufman, Z.; Arima, Y.; Oishi, K.; Chaves, S.; Nyawanda, B.; Al-Jarallah, R. A.; Kuri-Morales, P. A.; Matus, C. R.; Corona, M. E. J.; Burmaa, A.; Darmaa, O.; Obtel, M.; Cherkaoui, I.; van den Wijngaard, C. C.; van der Hoek, W.; Baker, M.; Bandaranayake, D.; Bissielo, A.; Huang, S.; Lopez, L.; Newbern, C.; Flem, E.; Grøneng, G. M.; Hauge, S.; de Cosío, F. G.; de Moltó, Y.; Castillo, L. M.; Cabello, M. A.; von Horoch, M.; Medina Osis, J.; Machado, A.; Nunes, B.; Rodrigues, A. P.; Rodrigues, E.; Calomfirescu, C.; Lupulescu, E.; Popescu, R.; Popovici, O.; Bogdanovic, D.; Kostic, M.; Lazarevic, K.; Milosevic, Z.; Todorovic, B.; Chen, M.; Cutter, J.; Lee, V.; Lin, R.; Ma, S.; Cohen, A. L.; Treurnicht, F.; Kim, W. J.; Delgado-Sanz, C.; de mateo Ontañón, S.; Larrauri, A.; León, I. L.; Vallejo, F.; Born, R.; Junker, C.; Koch, D.; Chuang, J.-H.; Huang, W.-T.; Kuo, H.-W.; Tsai, Y.-C.; Bundhamcharoen, K.; Chittaganpitch, M.; Green, H. K.; Pebody, R.; Goñi, N.; Chiparelli, H.; Brammer, L.; Mustaqim, D. Estimates of Global Seasonal Influenza-Associated Respiratory Mortality: A Modelling Study. *Lancet* **2018**, *391* (10127), 1285–1300.
- (11) Troeger, C. E.; Blacker, B. F.; Khalil, I. A.; Zimsen, S. R. M.; Albertson, S. B.; Abate, D.; Abdela, J.; Adhikari, T. B.; Aghayan, S. A.; Agrawal, S.; Ahmadi, A.; Aichour, A. N.; Aichour, I.; Aichour, M. T. E.; Al-Eyadhy, A.; Al-Raddadi, R. M.; Alahdab, F.; Alene, K. A.; Aljunid, S. M.; Alvis-Guzman, N.; Anber, N. H.; Anjomshoa, M.; Antonio, C. A. T.; Aremu, O.; Atalay, H. T.; Atique, S.; Attia, E. F.; Avokpaho, E. F. G. A.; Awasthi, A.; Babazadeh, A.; Badali, H.; Badawi, A.; Banoub, J. A. M.; Barac, A.; Bassat, Q.; Bedi, N.; Belachew, A. B.; Bennett, D. A.; Bhattacharyya, K.; Bhutta, Z. A.; Bijani, A.; Carvalho, F.; Castañeda-Orjuela, C. A.; Christopher, D. J.; Dandona, L.; Dandona, R.; Dang, A. K.; Daryani, A.; Degefa, M. G.; Demekke, F. M.; Dhimal, M.; Djalalinia, S.; Doku, D. T.; Dubey, M.; Dubljanin, E.; Duken, E. E.; Edessa, D.; El Sayed Zaki, M.; Fakhim, H.; Fernandes, E.; Fischer, F.; Flor, L. S.; Foreman, K. J.; Gebremichael, T. G.; Geremew, D.; Ghadiri, K.; Goulart, A. C.; Guo, J.; Ha, G. H.; Hailu, G. B.; Haj-Mirzaian, A.; Haj-Mirzaian, A.; Hamidi, S.; Hassen, H. Y.; Hoang, C. L.; Horita, N.; Hostiuc, M.; Irvani, S. S. N.; Jha, R. P.; Jonas, J. B.; Kahsay, A.; Karch, A.; Kasaeian, A.; Kassa, T. D.; Kefale, A. T.; Khader, Y. S.; Khan, E. A.; Khan, G.; Khan, M. N.; Khang, Y.-H.; Khoja, A. T.; Khubchandani, J.; Kimokoti, R. W.; Kisa, A.; Knibbs, L. D.; Kochhar, S.; Kosen, S.; Koul, P. A.; Koyanagi, A.; Kuate Defo, B.; Kumar, G. A.; Lal, D. K.; Lamichhane, P.; Leshargie, C. T.; Levi, M.; Li, S.; Macarayan, E. R. K.; Majdan, M.; Mehta, V.; Melese, A.; Memish, Z. A.; Mengistu, D. T.; Meretoja, T. J.; Mestrovic, T.; Miazgowski, B.; Milne, G. J.; Milosevic, B.; Mirzakhimov, E. M.; Moazen, B.; Mohammad, K. A.; Mohammed, S.; Monasta, L.; Morawska, L.; Mousavi, S. M.; Muhammed, O. S. S.; Murthy, S.; Mustafa, G.; Naheed, A.; Nguyen, H. L. T.; Nguyen, N. B.; Nguyen, S. H.; Nguyen, T. H.; Nisar, M. I.; Nixon, M. R.; Ogbo, F. A.; Olagunju, A. T.; Olagunju, T. O.; Oren, E.; Ortiz, J. R.; P A, M.; Pakhale, S.; Patel, S.; Paudel, D.; Pigott, D. M.; Postma, M. J.; Qorbani, M.; Rafay, A.; Rafiei, A.; Rahimi-Movaghar, V.; Rai, R. K.; Rezaei, M. S.; Roberts, N. L. S.; Ronfani, L.; Rubino, S.; Safari, S.; Safiri, S.; Saleem, Z.; Sambala, E. Z.; Samy, A. M.; Santric Milicevic, M. M.; Sartorius, B.; Sarvi, S.; Savic, M.; Sawhney, M.; Saxena, S.; Seyedmousavi, S.; Shaikh, M. A.; Sharif, M.; Sheikh, A.; Shigematsu, M.; Smith, D. L.; Somayaji, R.; Soriano, J. B.; Sreeramareddy, C. T.; Sufiyan, M. B.; Temsah, M.-H.; Tessema, B.; Teweldemedhin, M.; Tortajada-Girbés, M.; Tran, B. X.; Tran, K. B.; Tsadik, A. G.; Ukwaja, K. N.; Ullah, I.; Vasankari, T. J.; Vu, G. T.; Wada, F. W.; Waheed, Y.; West, T. E.; Wiyongse, C. S.; Yimer, E. M.; Yonemoto, N.; Zaidi, Z.; Vos, T.; Lim, S. S.; Murray, C. J. L.; Mokdad, A. H.; Hay, S. I.; Reiner, R. C. Mortality, Morbidity, and Hospitalisations Due to Influenza Lower Respiratory Tract Infections, 2017: An Analysis for the Global Burden of Disease Study 2017. *Lancet Respir Med.* **2019**, *7* (1), 69–89.
- (12) Li, Y.; Wong, T.; Chung, J.; Guo, Y. P.; Hu, J. Y.; Guan, Y. T.; Yao, L.; Song, Q. W.; Newton, E. In Vivo Protective Performance of

N95 Respirator and Surgical Facemask. *American Journal of Industrial Medicine* **2006**, *49* (12), 1056–1065.

(13) Collins, A. P.; Service, B. C.; Gupta, S.; Mubarak, N.; Zeini, I. M.; Osbahr, D. C.; Romeo, A. A. N95 Respirator and Surgical Mask Effectiveness against Respiratory Viral Illnesses in the Healthcare Setting: A Systematic Review and Meta-Analysis. *JACEP Open* **2021**, *2* (5), No. e12582.

(14) Rengasamy, S.; Miller, A.; Eimer, B. C.; Shaffer, R. E. Filtration Performance of FDA-Cleared Surgical Masks. *J. Int. Soc. Respir. Protect.* **2009**, *26* (3), 54–70.

(15) Fennelly, K. P. Particle Sizes of Infectious Aerosols: Implications for Infection Control. *Lancet Respiratory Medicine* **2020**, *8* (9), 914–924.

(16) Li, Y.; Leung, P.; Yao, L.; Song, Q. W.; Newton, E. Antimicrobial Effect of Surgical Masks Coated with Nanoparticles. *Journal of Hospital Infection* **2006**, *62* (1), 58–63.

(17) Kumaran, S.; Oh, E.; Han, S.; Choi, H. J. Photopolymerizable, Universal Antimicrobial Coating to Produce High-Performing, Multifunctional Face Masks. *Nano Lett.* **2021**, *21* (12), 5422–5429.

(18) Pullangott, G.; Kannan, U.; S, G.; Kiran, D. V.; Maliyekkal, S. M. A Comprehensive Review on Antimicrobial Face Masks: An Emerging Weapon in Fighting Pandemics. *RSC Adv.* **2021**, *11* (12), 6544–6576.

(19) De Maio, F.; Palmieri, V.; Babini, G.; Augello, A.; Palucci, I.; Perini, G.; Salustri, A.; Spilman, P.; De Spirito, M.; Sanguinetti, M.; Delogu, G.; Rizzi, L. G.; Cesareo, G.; Soon-Shiong, P.; Sali, M.; Papi, M. Graphene Nanoplatelet and Graphene Oxide Functionalization of Face Mask Materials Inhibits Infectivity of Trapped SARS-CoV-2. *iScience* **2021**, *24* (7), No. 102788.

(20) Hashmi, M.; Ullah, S.; Kim, I. S. Copper Oxide (CuO) Loaded Polyacrylonitrile (PAN) Nanofiber Membranes for Antimicrobial Breath Mask Applications. *Current Research in Biotechnology* **2019**, *1*, 1–10.

(21) Kumar, A.; Sharma, A.; Chen, Y.; Jones, M. M.; Vanyo, S. T.; Li, C.; Visser, M. B.; Mahajan, S. D.; Sharma, R. K.; Swihart, M. T. Copper@ZIF-8 Core-Shell Nanowires for Reusable Antimicrobial Face Masks. *Advance Functional Materials* **2021**, *31* (10), 2008054.

(22) Huang, L.; Xu, S.; Wang, Z.; Xue, K.; Su, J.; Song, Y.; Chen, S.; Zhu, C.; Tang, B. Z.; Ye, R. Self-Reporting and Photothermally Enhanced Rapid Bacterial Killing on a Laser-Induced Graphene Mask. *ACS Nano* **2020**, *14* (9), 12045–12053.

(23) Soni, R.; Joshi, S. R.; Karmacharya, M.; Min, H.; Kim, S. K.; Kumar, S.; Kim, G. H.; Cho, Y. K.; Lee, C. Y. Superhydrophobic and Self-Sterilizing Surgical Masks Spray-Coated with Carbon Nanotubes. *ACS Applied Nano Materials* **2021**, *4* (8), 8491–8499.

(24) Zhong, H.; Zhu, Z.; Lin, J.; Cheung, C. F.; Lu, V. L.; Yan, F.; Chan, C. Y.; Li, G. Reusable and Recyclable Graphene Masks with Outstanding Superhydrophobic and Photothermal Performances. *ACS Nano* **2020**, *14* (5), 6213–6221.

(25) Ragesh, P.; Anand Ganesh, V.; Nair, S. V.; Nair, A. S. A Review on “Self-Cleaning and Multifunctional Materials”. *Journal of Materials Chemistry A* **2014**, *2* (36), 14773–14797.

(26) Liu, G.; Nie, J.; Han, C.; Jiang, T.; Yang, Z.; Pang, Y.; Xu, L.; Guo, T.; Bu, T.; Zhang, C.; Wang, Z. L. Self-Powered Electrostatic Adsorption Face Mask Based on a Triboelectric Nanogenerator. *ACS Appl. Mater. Interfaces* **2018**, *10* (8), 7126–7133.

(27) Karimi Kisomi, M.; Seddighi, S.; Mohammadpour, R.; Rezaniakolaei, A. Enhancing Air Filtration Efficiency with Triboelectric Nanogenerators in Face Masks and Industrial Filters. *Nano Energy* **2023**, *112*, No. 108514.

(28) Salah, I.; Parkin, I. P.; Allan, E. Copper as an Antimicrobial Agent: Recent Advances. *RSC Adv.* **2021**, *11* (30), 18179–18186.

(29) Sudha, V. B. P.; Singh, K. O.; Prasad, S. R.; Venkatasubramanian, P. Killing of Enteric Bacteria in Drinking Water by a Copper Device for Use in the Home: Laboratory Evidence. *Transactions of the Royal Society of Tropical Medicine and Hygiene* **2009**, *103* (8), 819–822.

(30) Warnes, S. L.; Caves, V.; Keevil, C. W. Mechanism of Copper Surface Toxicity in *Escherichia Coli* O157:H7 and *Salmonella*

Involves Immediate Membrane Depolarization Followed by Slower Rate of DNA Destruction Which Differs from That Observed for Gram-Positive Bacteria. *Environmental Microbiology* **2012**, *14* (7), 1730–1743.

(31) Ermini, M. L.; Voliani, V. Antimicrobial Nano-Agents: The Copper Age. *ACS Nano* **2021**, *15* (4), 6008–6029.

(32) Noyce, J. O.; Michels, H.; Keevil, C. W. Potential Use of Copper Surfaces to Reduce Survival of Epidemic Methicillin-Resistant *Staphylococcus Aureus* in the Healthcare Environment. *Journal of Hospital Infection* **2006**, *63* (3), 289–297.

(33) Warnes, S. L.; Keevil, C. W.; Dozois, C. M. Lack of Involvement of Fenton Chemistry in Death of Methicillin-Resistant and Methicillin-Sensitive Strains of *Staphylococcus Aureus* and Destruction of Their Genomes on Wet or Dry Copper Alloy Surfaces. *Appl. Environ. Microbiol.* **2016**, *82* (7), 2132–2136.

(34) Che, W.; Xiao, Z.; Wang, Z.; Li, J.; Wang, H.; Wang, Y.; Xie, Y. Wood-Based Mesoporous Filter Decorated with Silver Nanoparticles for Water Purification. *ACS Sustainable Chem. Eng.* **2019**, *7* (5), 5134–5141.

(35) Ma, X.; Xiong, Y.; Liu, Y.; Han, J.; Duan, G.; Chen, Y.; He, S.; Mei, C.; Jiang, S.; Zhang, K. When MOFs Meet Wood: From Opportunities toward Applications. *Chem.* **2022**, *8* (9), 2342–2361.

(36) Su, M.; Zhang, R.; Li, H.; Jin, X.; Li, J.; Yue, X.; Qin, D. In Situ Deposition of MOF199 onto Hierarchical Structures of Bamboo and Wood and Their Antibacterial Properties. *RSC Adv.* **2019**, *9* (69), 40277–40285.

(37) Farid, T.; Wang, Y.; Rafiq, M. I.; Ali, A.; Tang, W. Porous Flexible Wood Scaffolds Designed for High-Performance Electrochemical Energy Storage. *ACS Sustainable Chem. Eng.* **2022**, *10* (21), 7078–7090.

(38) Fu, Q.; Chen, Y.; Sorieul, M. Wood-Based Flexible Electronics. *ACS Nano* **2020**, *14* (3), 3528–3538.

(39) Song, J.; Chen, C.; Wang, C.; Kuang, Y.; Li, Y.; Jiang, F.; Li, Y.; Hitz, E.; Zhang, Y.; Liu, B.; Gong, A.; Bian, H.; Zhu, J. Y.; Zhang, J.; Li, J.; Hu, L. Superflexible Wood. *ACS Appl. Mater. Interfaces* **2017**, *9* (28), 23520–23527.

(40) Zia, A.; Neupane, M.; McGlone, A.; He, R.; Xin, R.; Liu, Y.; Yan, Q.; Wang, J.; Li, L.; Cai, Z.; Dong, P.; Yang, Y. Coupling metal-organic frameworks and wood-based carbon for water remediation. *Nano Res.* **2024**, *17* (6), 5661–5669.

(41) Meng, Y.; Neupane, M.; Glenn, D. M.; Jana, A.; Wang, W.; Zhao, H.; Qian, J.; Yang, Y.; Wang, L. C.; Snyder, S. W. Balsa Wood-Derived Carbon Enriched with Hydroxyl Functional Groups for Efficient CO₂ Sorption. *ACS Sustainable Chem. Eng.* **2025**, *13* (16), 5974–5984.

(42) Borrega, M.; Ahvenainen, P.; Serimaa, R.; Gibson, L. Composition and Structure of Balsa (*Ochroma Pyramidale*) Wood. *Wood Science and Technology* **2015**, *49* (2), 403–420.

(43) Aro, T.; Fatehi, P. Production and Application of Lignosulfonates and Sulfonated Lignin. *ChemSusChem* **2017**, *10* (9), 1861–1877.

(44) Milojković, J.; Bijelić, I.; Vranić, N.; Radovanović, N.; Živković, M. Determining Elastic Modulus of the Material by Measuring the Deflection of the Beam Loaded in Bending. *Tehnicky vjesnik* **2017**, *24* (4), 1227–1234.