Facile preparation of antibacterial MOF-fabric systems for functional protective wearables

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Abstract
Metal-organic frameworks (MOFs) have shown numerous potentials as promising materials to address real-world problems. However, their practical utilization in commercial products was largely limited by the lack of downstream processing methodologies to transform MOF powders into functional products. In this study, a commercially viable solution for the general synthesis of MOF-fabric composites was introduced. On account of coordination bonding between poly(acrylic acid) and MOF substrates, MOF powders securely adhered onto the surface of fabric materials via a drip cast method to give MOF-fabric composites easily. This strategy can be applied to different MOF types, as well as a wide variety of fabric materials. The prepared materials showed excellent bacterial killing efficacy attributed to the embedded HKUST-1 MOF. In light of the recent coronavirus disease 2019 pandemic, this methodology could enable the large-scale fabrication of essential MOF-based personal protective wearables (e.g., clothing and masks) for use by healthcare professionals.

KEYWORDS
antibacterial properties, cloth materials, composite processing, metal-organic frameworks, protective wearables

Wei Liang Teo and Jiawei Liu contributed equally to this study.

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1 | INTRODUCTION

Over the years, metal-organic frameworks (MOFs) have established themselves as a unique class of porous material with exceptionally high surface area, rich functionalities, and superior customizability.\(^1\) By different permutation of metallic and organic precursors, a large number of MOFs with unique properties can be derived.\(^3\)\(^-\)\(^5\) Furthermore, the as-synthesized MOFs can be subjected to postsynthetic modification (PSMs) to induce additional functionalities.\(^6\)\(^-\)\(^7\) With such flexibility and modifiability, it is not surprising that MOFs are utilized in a great number of areas, such as gas capture/storage,\(^8\)\(^-\)\(^11\) separation,\(^12\) sensing,\(^13\) catalysis,\(^14\)\(^-\)\(^16\) photonic,\(^16\)\(^-\)\(^17\) battery,\(^18\)\(^-\)\(^19\) biomedicine,\(^20\) and water harvesting.\(^21\)

While innovations for MOF applications are rapidly growing, translational technology to develop MOFs into useable products is still lacking.\(^22\)\(^-\)\(^25\) Despite the emergence of start-ups that specialize in MOF-based materials for commercial use, such as Trupick and NuMat Technologies,\(^26\)\(^-\)\(^27\) the commercialization of MOF products is still in its infancy. There is a pressing need to develop new methodologies for the preparation of MOF-based composite materials in general.\(^28\)\(^-\)\(^32\) Many significant developments were observed to address this study gap. In 2016, Cohen et al. have introduced a general method to yield high loading MOF mixed-matrix membranes.\(^3\) The as-prepared material was shown to be useful for dye separation and can even undergo PSMS to gain additional functionalities. The same group went on to develop the processing technique for such composites.\(^34\) In 2017, Wang et al. have developed a method to fabricate MOF hollow tubes for the mitigation of pollutants.\(^35\) The synthesized materials are robust, and their shapes and sizes can be varied by casting in different molds. Recently, Queen et al. have successfully fabricated MOF-beads from a dripping technique.\(^36\) The prepared beads were utilized for effective heavy metal ion removal from water. These studies show that there is a growing interest in developing useful methodologies to derive MOF-composite products from their powdered form. Despite these breakthrough studies, downstream processing of MOFs to fabricate commercially useable MOF-based materials is often overshadowed, and thus, still remains relatively unexplored.

For MOF-fabric composites, several notable studies were carried out as well.\(^31\) In 2014, Wang and coworkers have successfully utilized an electrospinning technique to coat fibers with a MOF-polymer mixture.\(^37\) The resultant product was used to remove particulate matter from air. In 2019, Wang et al. introduced a heat press method to directly synthesize MOFs onto fabrics from their solid precursors.\(^38\) In the same year, Farha and coworkers introduced MOF-808 onto fibers via a dip-coating method.\(^39\) These studies provided a good foundation to produce MOF-fabric composite materials.\(^40\)\(^-\)\(^42\) However, most of the methods are time-consuming, and could not be efficiently employed for mass production of the composite materials. Most studies were also limited in their scope, and hence not applicable to a wide range of MOF and fabric materials. Furthermore, effective control over the quantity of MOF loaded has rarely been demonstrated so far. As such, the search for a practical large-scale methodology to effectively produce MOF-based fabric materials continues.

With advancements in biomedical science and healthcare, the need for functional materials to keep us safe from microbes is a pressing concern for humanity. In light of the recent coronavirus disease pandemic, it is even more crucial to develop new functional protective wearables with antimicrobial properties to sufficiently eliminate biohazardous threats that medical professionals faced.\(^43\) The incorporation of functional MOFs into protective wearables is a promising strategy to address this problem.\(^44\)\(^-\)\(^46\) Due to the customizability of MOFs, they can be strategically designed and optimized for the targeted killing of harmful microbes.\(^47\) In addition, their porous nature can also be utilized to encapsulate other antimicrobial species, making them more effective as next-generation smart systems.\(^48\) It is crucial for MOFs to be tightly bounded to these protective wearables to avoid the detachment of MOFs during practical usage. Thus, strong adhesion between MOFs and fabric substrates is an essential prerequisite to be considered during material design and construction.

In this study, we demonstrated a facile and general strategy for the production of MOF-fiber composites by dip-coating a mixture of MOFs and poly(acrylic acid) (PAA) onto fabrics (Scheme 1). The amounts of MOF loaded were well controlled by adjusting the MOF-PAA mixture, and the as-prepared fabrics were easily dried after the treatment to give functional MOF-fabric composites capable of eradicating bacterial strains. This method is versatile and can be applied to a wide range of MOFs and fabric materials. Thanks to the PAA added, MOFs and fabric are strongly bound together to give a material suitable for use as protective wearables (e.g., clothing and masks). The preparation of composite materials can be achieved in a short time span, allowing for rapid production. This efficient method is promising for the industrial production of highly functional MOF-based products. To the best of our knowledge, this unprecedented methodology addressed most of the common shortfalls associated with the commercial production of MOF-fabric composites, providing a simple and elegant solution to generate functional materials with real-world applications.
2 | EXPERIMENTAL SECTION

2.1 | Synthesis of HKUST-1

NaOH (497 mg, 12.4 mmol) and trimesic acid (870 mg, 4.1 mmol) were added into deionized water (20 ml). A solution of Cu(NO$_3$)$_2$·3H$_2$O (1.5 g, 6.2 mmol) dissolved in EtOH (15 ml) was added. Precipitates emerged immediately and the mixture was stirred briefly before the solid was separated via centrifugation. The solid was washed three times with EtOH before drying in a desiccator at room temperature overnight to give HKUST-1 as a blue powder (~84% yield).49

2.2 | Synthesis of MIL-100(Fe)

FeSO$_4$·7H$_2$O (3.41 g, 12.3 mmol) was dissolved in deionized water (100 ml). A solution of NaOH (982 mg, 24.6 mmol) and trimesic acid (1.72 g, 8.2 mmol) in deionized water (30 ml) was added dropwise and the solution was stirred for 24 h. The resultant mixture was washed three times with H$_2$O and three times with EtOH, followed by drying in an 80°C oven to give MIL-100(Fe) as a brown powder (~73% yield).50

2.3 | Synthesis of MIL-101(Cr)

Benzene-1,4-dicarboxylic acid (332 mg, 2 mmol), Cr(NO$_3$)$_3$·9H$_2$O (800 mg, 2 mmol), and 48% HF in H$_2$O (40 μl, 2 mmol) were added into distilled water (9.6 ml) in Teflon-lined autoclave. The sealed mixture was heated in an oven at 200°C for 8 h. The resultant mixture was washed three times with DMF and then heated in EtOH (9 ml) at 80°C for 12 h. The heated mixture was then washed three times with H$_2$O and three times with EtOH, before drying in a desiccator overnight to give MIL-101(Cr) as a green powder (~50% yield).51

2.4 | Synthesis of UiO-66

ZrCl$_4$ (23.3 mg, 0.1 mmol), benzene-1,4-dicarboxylic acid (16.6 mg, 0.1 mmol), and acetic acid (1.37 ml) were dissolved in DMF (10 ml). The mixture was heated at 120°C for 24 h. The resultant slurry was washed three times with DMF and three times with MeOH before drying in 150°C vacuum oven to give UiO-66 as a white powder (~77% yield).52

2.5 | Preparation of MOF/Fabric composites

Cloth materials were cut into 4 × 4 cm pieces (~120 mg for cotton, ~150 mg for polyester, and ~400 mg for nylon), soaked in EtOH, and dried in the oven before use. MOF powder (type and mass used as denoted in the name of the composite) and PAA of equal mass were mixed in EtOH (400 μl) to form a MOF ink. The prepared MOF ink was dripped onto the fabric cloth and dried with N$_2$ gas to give the composite.

2.6 | Synthesis of HKUST-1/mask composite

HKUST-1 (1 g) and PAA (1 g) were dissolved in EtOH (10 ml). The resultant suspension was coated onto a
commercial respiratory dust mask, dried briefly with N₂, before desiccating at room temperature.

### 2.7 Bacterial culture

*Escherichia coli* and *Staphylococcus aureus* were incubated in LB medium with shaking at 37°C for 18 h. The concentration of bacteria was calculated by measuring the optical density at 600 nm (OD₆₀₀) using an UV–vis spectrometer. The bacteria suspension was then diluted to the appropriate level for further antibacterial experiments.

### 2.8 Antibacterial property of different materials

The bacterial suspension (200 μl, 1 × 10⁶ CFU/ml) was spread onto an LB plate. Different cotton samples of 1 × 1 cm (HKUST-1/Cotton-40 mg, MIL-100(Fe)/Cotton-40 mg, MIL-101(Cr)/Cotton-40 mg, UiO-66/Cotton-40 mg, PAA/Cotton-20 mg, and Blank Cotton) were pasted onto the LB plate before they were cultivated at 37°C for 18 h.

### 2.9 Antibacterial property of HKUST-1/Cotton with different concentrations

The bacterial suspension (200 μl, 1 × 10⁶ CFU/ml) was spread onto an LB plate. Different cotton samples of 1 × 1 cm (HKUST-1/Cotton-x mg, x = 0, 5, 10, 20, and 40) were pasted onto the LB plate before they were cultivated at 37°C for 18 h.

### 2.10 Time-related antibacterial property of HKUST-1/Cotton

Three doses of bacterial suspension (1 × 10⁸ CFU/ml) were sprayed onto 1 × 1 cm HKUST-1/Cotton-40 mg and blank cotton using a spray bottle, respectively. The bacteria on the cotton were collected by swabbing the cotton strips with a wet cotton swab at different time intervals (10, 20, and 30 min) and submerging the contaminated swab in deionized water (200 μl). The solutions were diluted 1000 times and dripped onto LB plates to cultivate at 37°C for 18 h.

### 2.11 Antibacterial property of HKUST-1/mask

Three doses of bacterial suspension (1 × 10⁵ CFU/ml) were sprayed onto the surface of HKUST-1/Mask and blank mask using a spray bottle, respectively. The bacteria on the masks were collected by swabbing the cotton strips with a wet cotton swab at different time intervals (10 and 20 min) and submerging the contaminated swab in deionized water (200 μl). The solutions (150 μl) were dripped onto LB plates to cultivate at 37°C for 18 h.

### 3 RESULTS AND DISCUSSION

#### 3.1 Initial hypothesis and density functional theory calculation

To achieve a practical and scalable methodology for the fabrication of MOF-fabric composites, we proposed to develop a means to coat raw MOF powder directly onto fabric substrates. This process eliminates the long preparation time typically associated with in situ growth of MOFs onto substrates⁴⁰–⁴² and allows for more variety of MOFs to be coated, given that protocols for the preparation of MOF powders are more established. PAA was chosen to be the binder as it is a cheap and commercially available polymer used for textile processing.⁵³ Due to the abundance of carboxylic acid groups present, we hypothesized that PAA would coordinate with valence metal sites on the surface of MOFs and effectively bind them to the fabric substrates to give functional composite materials. To establish control over the loading amount for MOFs, we plan to take advantage of the adsorbing nature of fabrics and employ a drip cast methodology. The resultant products can be quickly dried under gas flow to vaporize the volatile solvents, leaving MOFs and PAA securely attached to the fabric substrates.

To verify our hypothesis, density functional theory (DFT) calculations were firstly conducted. Details of DFT calculations are described in the ESI. HKUST-1 (Figure 1A) and a PAA moiety consisting of two repeating units were chosen to model possible interactions between MOF surface and PAA substrate. The two oxygen atoms of the carboxylic group in PAA moiety form coordination bonds on HKUST-1 surface (Figure 1B). The bonding energy was calculated to be −2.086 eV, with 0.594 e⁻ gained by each oxygen atom (Figure 1C). Based on our calculations, it is feasible for PAA to bind to the copper atoms on the HKUST-1 surface to give PAA-modified HKUST-1. In addition, the affinity between fabric substrate and pristine HKUST-1 or PAA-modified HKUST-1 was also determined. Glucose, a monomer of cellulose-derived cotton, was used to represent fabric substrate, and the adsorption energy was calculated based on its interaction with either pristine HKUST-1 or PAA-modified HKUST-1. The adsorption energy between glucose and PAA-modified HKUST-1 is −0.798 eV, which...
is significantly larger than that between glucose and pristine HKUST-1 at $-0.225 \text{ eV}$ (Figures 1D,E). This result indicates that surface modification with PAA enhances the affinity between HKUST-1 and fabric substrate, allowing for better adhesion during the formation of MOF-fabric composites.

### 3.2 Preparation of MOF-fabric composites

A preliminary study was conducted using HKUST-1 and cotton fabric (Figure 2). Pristine powdered HKUST-1 was synthesized and characterized before coating onto fabric substrates (Figure 2C and Figures S1–S4). When the prepared HKUST-1 was mixed with commercially available short-chain PAA, a suspension mixture was obtained, which can be easily dripped onto the cotton fabric substrate. By premixing different amounts of HKUST-1 and PAA, HKUST-1/Cotton-$x$ mg ($x = 0, 5, 10, 20,$ and 40) composites were obtained. Beyond HKUST-1/Cotton-40 mg, the composites start to lose flexibility, and visible cracking and dislodgment of the coated materials can be observed (Figure S5). When PAA was not utilized, HKUST-1 powder also dislodged easily from the cotton fabric scaffold (Figure S5). The as-prepared materials exhibit an increasing shade of blue as the loading amount increases, suggesting the successful incorporation of different amounts of MOFs onto the cotton substrate (Figure 2A). From the powder X-ray diffraction (PXRD) patterns, an increase in diffraction peak intensities associated with HKUST-1 can be seen as MOF loading increases, supporting the initial visual observation for increasing MOF loading across the samples (Figure 2D). Similarly, attenuated total reflection-Fourier transform infrared (ATR-FTIR) measurements show increasing intensity at 1369 cm$^{-1}$ (-COO from MOFs) relative to the 900–1085 cm$^{-1}$ region (-CO from cotton), further proving that the loading amount was precisely controlled for the different samples (Figure 2E). Scanning electron microscope (SEM) images also show that the amount of MOF present on the surface of cotton fibers increases across the samples (Figure 2A). Thus, by using a drip cast method, the amount of MOFs loaded onto fabric materials can be precisely controlled.

HKUST-1/Cotton-40 mg was further investigated to shed light on the resultant properties of the MOF-cotton fabric materials. The weight difference between HKUST-1/Cotton-40 mg and cotton suggests a high average loading efficiency of 85%, not accounting for mass transfer loss, showing that this is a very efficient loading method for the fabrication of MOF-based fiber composites. The resultant fabric retained the physical properties of the fabric substrates, which were able to withstand rolling, bending, and cutting without any visible dislodgement of coated substance (Figure 2B). Comparing the PXRD patterns and ATR-FTIR spectra of HKUST-1/Cotton-40 mg, pristine HKUST-1 powder and cotton cloth coated with PAA revealed that the resultant composite possesses characteristic patterns of
both components (Figures 3A,B). This result suggests that the process does not significantly alter and compromise the structural integrity of HKUST-1 MOF. Well-defined HKUST-1 particles were observed by SEM on HKUST-1/Cotton-40 mg, with no observable morphological change as compared to the pristine HKUST-1 powder (Figure 3C and Figures S4 and S6). Energy-dispersive X-ray spectroscopy (EDX) of HKUST-1/Cotton-40 mg also revealed the presence of Cu from HKUST-1, indicating the successful coating of the cotton substrate with MOFs (Figure 3D). N$_2$ adsorption/desorption studies (Figure S7) showed that the composite possesses a slight increase in porosity (BET surface area = 36 m$^2$/g) over the PAA coated cotton substrate (BET surface area = 7 m$^2$/g). Compared to the pristine HKUST-1 powder, a significant decrease in porosity was observed, possibly due to the weight contribution by the fabric substrate. A similar observation was seen from the thermogravimetric analysis (TGA), with no significant difference between HKUST-1/Cotton-40 mg and PAA coated cotton substrate (Figure S8). By combining HKUST-1 with the cotton substrate, the resultant material retained the flexible property of the cloth while possessing additional functionalities induced by HKUST-1, giving a novel MOF-based fabric composite.

HKUST-1 was also coated onto other fabric materials, such as polyester and nylon. A similar protocol was utilized for the fabrication of HKUST-1/Polyester-50 mg and HKUST-1/Nylon-135 mg. Due to the weight differences for the different types of cloth, HKUST-1 and PAA added were adjusted accordingly to ensure that the theoretical wt% of loading remained constant. Similar to HKUST-1/Cotton-40 mg, both polyester and nylon substrates were dyed blue after the coating, thanks to HKUST-1 used. PXRD (Figures 3E,I) and ATR-FTIR measurements (Figures 3F,J) of the two samples showed similar observations as HKUST-1/Cotton-40 mg, with characteristic patterns of the composites matching to that of respective components. SEM images also indicated that HKUST-1 particles were well coated onto the fibers, regardless of the type of fabric used (Figures 3G,K and Figure S9).
EDX measurements revealed the presence of Cu from HKUST-1 on both polyester and nylon fiber strands (Figures 3H,L). Unlike HKUST-1/Cotton-40 mg, N₂ adsorption/desorption studies (Figure S7) on the polyester and nylon composites presented no significant gas uptake, further proving the initial hypothesis that the weight of the fabric used significantly affects the porosity. TGA measurements further confirmed this observation (Figure S8). As such, it is reasonable to conclude that the applied strategy is not limited to cotton fabric, with the potential to be extended to other fabric materials as well.

This strategy was also demonstrated using other MOF types to further establish its generality. Three other MOFs (i.e., MIL-100(Fe), MIL-101(Cr), and UiO-66) were chosen to expand the scope of this study. Pristine powdered MIL-100(Fe), MIL-101(Cr), and UiO-66 were prepared and characterized before they were coated onto fabric substrates (Figures 4A,E,I and Figures S1–S4). MIL-100(Fe)/Cotton-40 mg, MIL-101(Cr)/Cotton-40 mg, and UiO-66/Cotton-40 mg were then fabricated using a similar protocol as HKUST-1/Cotton-40 mg. Like the HKUST-1 fabric, the other MOF fabrics adopted color from the MOF samples, suggesting the successful embedding of the various MOF materials onto the cotton substrates. PXRD (Figures 4B,F,J) and ATR-FTIR measurements (Figures 4C,G,K) of the various composites showed characteristic patterns of both MOFs and fabrics used, indicating that the various MOFs were attached to the fabric substrates. SEM images also showed that the various MOF particles were well coated onto the fibers (Figures 4D,H,L). EDX scan further supported this conclusion, with different metallic elements from their parent MOFs presenting on the fiber strands (Figures 4D,H,L). N₂ adsorption/desorption studies (Figure S7) indicated an observable difference in gas uptake for MIL-101(Cr)/Cotton-40 mg as compared to the PAA coated cotton substrate, while the negligible difference was observed for MIL-100(Fe)/Cotton-40 mg and UiO-66/Cotton-40 mg. This result can be rationalized because pristine MIL-101(Cr) has significantly higher porosity compared to the other MOFs used, which compensated for the weight of the cotton fabric utilized. However, TGA measurements revealed no significant
difference for these samples (Figure S8). Nevertheless, it is clear that this strategy of producing MOF-fabric composites is applicable to various MOF types, proving that it is a general strategy adaptable to various fabrics and MOF materials.

3.3 | Antibacterial studies

To illustrate the functionalities of our MOF-fabric composites, we tested them for their antibacterial properties. Cotton and PAA-coated cotton samples were also prepared as controls. The various samples were incubated on a Luria broth plate coated with a layer of *Escherichia coli* (*E. Coli*). The preliminary result indicates that HKUST-1/Cotton-40 mg is an excellent system for antibacterial study, as there is a clear and observable inhibition region without bacteria colony growth surrounding the composite material after the incubation period (Figure 5A). Compared to the controls, it can be concluded that the antibacterial properties exhibited by HKUST-1/Cotton-40 mg are a result of the HKUST-1 presence, as neither the cotton nor the PAA coated cotton showed a similar result. Also, the MOF-fabric composites were further tested with a Gram-positive bacterium, that is, *Staphylococcus aureus* (*S. Aureus*), giving similar results (Figure 5B). This outcome shows that the antibacterial property of our MOF-fabric composite is general.

Given the success of our initial screening studies, HKUST-1/Cotton composite was selected for further investigations to quantify its antibacterial effect. A detailed analysis using HKUST-1/Cotton-x mg (*x* = 5, 10, 20, and 40) samples shows that the antibacterial properties of the composite materials varied according to the amount of HKUST-1 loaded. Strips of HKUST-1/Cotton-x mg were incubated in agar plates with *E. Coli*. A gradual increase in the size of the rings surrounding HKUST-1/Cotton samples upon increasing the HKUST-1 content further proves that the HKUST-1 content in the composites is responsible for inhibiting the growth of bacteria (Figure 5D and Figure S10). This conclusion agrees with literature findings, as an HKUST-1 variation Cu$_2$(NH$_2$BTC)$_2$ MOF was shown to be effective against bacteria strains. Also, several studies have established the antibacterial properties of HKUST-1. \(^{45,55}\)
We further tested the time-dependent killing efficiency of HKUST-1/Cotton-40 mg by spraying a stock solution of *E. Coli* onto the composite directly before incubation. Samples were taken using cotton swabs at different time intervals to determine the amount of living bacteria present. This process allows for more realistic testing of our materials to gauge their performance under real-life scenarios (e.g., sneezing). As time elapsed, a gradual decrease in the number of bacteria colonies was observed (Figures 5C,E and Figures S11 and S12). Most of the *E. Coli* sprayed onto the fabrics were killed, and by 30 min, the *E. Coli* deposited was almost completely eradicated. This observation shows that the HKUST-1/Cotton sample is a very effective antibacterial material against contaminated bacterial droplets in air.

To better understand the interactions between our prepared MOF/cotton fabrics and *E. Coli*, SEM was utilized for imaging. *E. Coli* incubated with HKUST-1/Cotton-40 mg showed apoptosis of bacteria (Figures 5K,L), as compared to nontreated cotton cloth (Figures 5I,J), further establishing the bacteria-killing efficacy of the prepared composite materials. This finding has huge implications for future medical and healthcare applications, as this methodology can be utilized to fabricate protective wearables for frontline healthcare workers.

To further show that the coating strategy is effective for the fabrication of protective wearables, we coated a commercial mask with the same solution containing HKUST-1 and PAA to give an HKUST-1/mask composite (Figure 5F). Similarly, a stock solution of bacteria was sprayed onto the coated mask to simulate contaminated...

**FIGURE 5** Initial screening of various fabric substrates for (A) *Escherichia coli (E. Coli)* and (B) *Staphylococcus aureus (S. Aureus)* killing efficacies. (C) Bacteria killing efficacy of HKUST/Cotton-40 mg across different time periods. (D) Inhibition areas of different HKUST/Cotton-x mg (x = 5, 10, 20, and 40) samples. (E) Survival rates of bacteria across different incubation periods on HKUST/Cotton-40 mg. (F) Photo of user donning HKUST-1 coated mask. (G) Bacteria present on blank mask after 20 min. (H) Bacteria present on HKUST-1 coated mask after 20 min. (I) Morphology of bacteria incubated with blank cotton fabric. (J) Enlarged image of bacteria incubated with blank cotton fabric. (K) Morphology of bacteria incubated with HKUST/Cotton-40 mg fabric. (L) Enlarged image of bacteria incubated with HKUST/Cotton-40 mg fabric
droplets in air. Compared to the control, bacteria growth was inhibited due to the presence of HKUST-1 on the mask, granting its antibacterial properties. A distinct difference can be observed after 20 min of incubation, with high efficiency of bacteria-killing for the HKUST-1 coated mask (Figures 5G,H and Figure S13). The experiment was repeated a total of three times with no significant decrease in the antibacterial properties of HKUST-1/mask composite, suggesting good reusability of our material for practical use. Once again, our method was demonstrated to be versatile, not solely limited to the production of functional cloth fabrics. This methodology can be utilized for the commercial manufacturing of useful antibacterial wearables in general, which is essential to help healthcare professionals in times of crisis.

4 | CONCLUSION

In this study, we have introduced a practical strategy to coat MOFs onto fabric materials using PAA as the binder. The method has been demonstrated to be fast and simple for the downstream processing of powdered MOF precursors into usable products. Not only can this method control the amount of MOFs loaded onto fabrics, it can also be applied to coat a wide variety of MOFs securely onto different fabric substrates. The resultant composite materials retain the flexibility imparted by the fabric while possessing unique properties due to the MOFs introduced. These MOF-fabric composites are generally stable and can be stored for a long period of time. One of the composites prepared, HKUST-1/Cotton has been demonstrated to have strong antibacterial properties, thanks to the MOF presence. This versatile method can be readily scaled up for the commercial production of MOF-coated products, such as protective wearables for healthcare workers, due to its simple and efficient coating process. Toward practical uses, detailed evaluations of the obtained MOF-fabric composite materials such as their wear/moisture resistance and long-term toxicity will be conducted in our follow-up research. We envision that this unprecedented methodology will revolutionize the industrial processing of MOFs in combination with fabric materials, to give useful and functional MOF-based composites in the future.

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CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

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**SUPPORTING INFORMATION**

Additional Supporting Information may be found online in the supporting information tab for this article.

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