ABSTRACT: Poly(methyl methacrylate) (PMMA) is a thermoplastic polyester with excellent properties such as lightweight, low price, biocompatibility, and so on. However, its extensive utilization is restricted by the deficiencies of brittleness and poor mechanical properties. In this study, high-performance PMMA films enhanced by methylcellulose (MC) were fabricated by a simple procedure at ambient temperatures. The effects of PMMA/MC mass ratio and thermal compression treatment on mechanical properties (tensile strength and elongation) were systematically investigated. The PMMA/MC films showed remarkably enhanced mechanical properties compared with neat PMMA. The tensile strengths of the PMMA/MC (3:97) and PMMA/MC (1:1) films are higher than that of the PMMA/MC (9:1) film by about 471 and 83%, respectively. The mechanical properties were also improved after thermal compression treatment. Importantly, the PMMA/MC films could be recovered and reused. In addition, the morphologies, crystalline state, and chemical structures of the films were investigated by scanning electron microscopy, X-ray diffraction, and $^{13}$C NMR spectroscopy. The films are expected to be used as sustainable and potential alternatives to petroleum-based polymer film products because of their simple preparation procedure, high-performance mechanical properties, excellent recycling, eco-friendly features, and scale manufacture.

INTRODUCTION

Poly(methyl methacrylate) (PMMA) is a thermoplastic polyester with outstanding characteristics such as lightweight, low price, easy processing, excellent transparency, and biocompatibility.$^{1,2}$ Based on these excellent properties, it is widely used for the production of medicine and dentistry materials,$^3$ photosensitive plastics,$^4$ electrically conductive composite materials,$^5,6$ and thermally conductive composite materials.$^7$ Very recently, it has been reported that active food-packaging films with antibacterial activities can be fabricated via the microfluidic spinning technology using the mixed solution of konjac glucomannan, PMMA, and chlorogenic acid.$^8$ However, the deficiencies of PMMA such as brittleness and poor mechanical properties are still major limitations or a disadvantage for its extensive application.$^2,9−11$ To overcome the issues, some investigations have been completed to develop PMMA composites in which reinforcement components such as carbon nanotubes, ultralong chitin nanofibers, and cellulose nanocrystals have been filled to improve the mechanical properties.$^2,9−11$ However, certain drawbacks still exist. For example, the mechanical properties of PMMA composites cannot be enhanced markedly; the uses of nanofillers can result in high prices of PMMA composites, which make the composites less competitive; quite complex and time-consuming preparation procedures of some PMMA composites are also limiting factors for scale-up production. Therefore, it is of great demand to develop high-performance PMMA composites using low cost resources as well as a simple preparation procedure.

Over the past years, the rapid exhaustion of fossil resources and environmental pollution caused by the usage of fossil-based products urgently demand new alternatives to satisfy sustainable development and improve the ecological environment.$^{12−15}$ Methylcellulose (MC) is a biopolymer derived from the substitution of hydrogen atoms of the hydroxyl residues of the cellulose backbone by methyl groups.$^{16−19}$ MC possesses many attractive properties of excellent film-making capability, good biodegradability, nontoxicity, and strong mechanical properties.$^{20,21}$ Therefore, it has been used in...
preparing biodegradable composite films by blending with sodium alginate, chitosan, wheat gluten, and chitosan ascorbate.22 In addition, MC is also more commercially available and cheaper than nano fillers.26 Based on these advantages, it is clear that MC is a good candidate for preparing eco-friendly PMMA/MC composites, especially against the background of concerns about petroleum-based polymer composites which are difficult to degrade and lead to inevitable environmental pollution.27−29 However, to the best of our knowledge, no literature is available on the PMMA/MC composite material and its properties until now.

Herein, the overarching objective of this study was to develop a simple approach for the scale-up preparation of PMMA films by hybridization with MC. Furthermore, scanning electron microscopy (SEM), X-ray diffraction (XRD), 13C nuclear magnetic resonance (NMR) spectroscopy, and mechanical tests were used to study the microstructure, crystalline state, and mechanical properties of these films. Moreover, the effect of thermal compression on the mechanical properties and recyclability of the PMMA/MC films were also estimated.

■ MATERIALS AND METHODS

Materials and Fabrication of PMMA/MC Films. PMMA ($M_W = 99,200$) was purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. MC (viscosity: 1600 cPs) was from Alfa Aesar (Shanghai, China). Hexafluoroisopropanol (HFIP) (99.5%) was purchased from Aladdin Biochemical Technology Co., Ltd. (Shanghai, China).

To obtain a PMMA/MC solution, some solvents such as HFIP, dichloromethane, dimethylformamide, 1,4-dioxane, dimethyl sulfoxide, dimethyacetamide, 1-methylpyrrolidone, and tetrahydrofuran were tested for dissolving PMMA and MC. It was found that only HFIP could simultaneously dissolve PMMA and MC. Therefore, HFIP was employed as a solvent of PMMA and MC. PMMA and MC are easily dissolved in HFIP at ambient temperatures. This indicates a scale-up manufacture possibility of the PMMA/MC composite.

As an experimental representative, the PMMA/MC (9:1) film was fabricated as follows. The PMMA/MC/HFIP solution was obtained by stirring the MC, PMMA, and HFIP mixture in a flask with a magneton at ambient temperatures. The total solubility of MC and PMMA in HFIP was about 1.5 g/100 g. The flask was placed in an ultrasonic apparatus for about 30 min to desiccate the bubbles in the PMMA/MC/HFIP solution. Then, the PMMA/MC/HFIP solution was transferred to a glass mold (10 cm × 10 cm). A PMMA/MC (9:1) film was obtained after HFIP volatilization, where 9:1 represented the PMMA/MC mass ratio. The resultant PMMA/MC (9:1) film was dried in a vacuum oven at 50 °C for the complete evaporation of the HFIP residual. The other PMMA/MC films with different PMMA/MC mass ratios were similarly prepared.

Characterization of the PMMA/MC Composite Film. SEM was performed on a JEOL JSM-6390LV scanning electron microscope. The sample film was immersed in liquid nitrogen and then snapped, and the fracture surface was...
sprayed with gold. Solid-state $^{13}$C NMR was performed on a 400 MHz NMR spectrometer (Bruker Avance III, Germany). Prior to measurements, the cellulose/PMMA films were ground with a mortar and pestle to obtain powders, and the size of the powders was less than 1 mm. XRD analysis was performed on a D8 Advance diffraction spectrometer (40 kV, 2° min$^{-1}$, $\lambda = 1.54$ cS, Bruker). A WDW-10 microcomputer control electronic universal tensile tester (Jinan Yinuo Century Testing Machine Co., Ltd., Jinan, China) was employed to determine the tensile strength and elongation at break based on ISO 527-3, 1995 (E) with a speed of 2 mm min$^{-1}$. The average value of the five measurements was taken for each sample.

Hot-Press Measurements. The hot-press measurements of the PMMA/MC films were performed on an electrothermal semi-automatic plate vulcanizing machine (63T, Chengdu Lishi Hydraulic Manufacturing Co., Ltd., Chengdu, China). The PMMA/MC film was pressed at 10 MPa and a given temperature for 10 min and then cooled to room temperature at 10 MPa. The hot-press film was used for the tensile strength and elongation at break measurements.

Recovery Experiment of the PMMA/MC Film. Typically, a homogeneous PMMA/MC/HFIP solution was obtained by dissolving the PMMA/MC (1:1) film in HFIP. This homogeneous solution was employed to reprepare the PMMA/MC film using the aforementioned preparation method. The determination of the tensile strength and elongation at break of the refabricated PMMA/MC (1:1) film was performed as mentioned above.

## RESULTS AND DISCUSSION

Morphology Analysis. Figure 1 presents the SEM images of the PMMA/MC and MC films. For the PMMA/MC films with varying PMMA/MC mass ratios, a distinctly different morphological structure is observed. Many voids can be observed in PMMA/MC (9:1) and PMMA/MC (7:3) films. As the MC content in the PMMA/MC composite is increased further, spherical PMMA obviously agglomerates in the PMMA/MC (1:1), PMMA/MC (3:7), and PMMA/MC (1:9) films. By comparison, PMMA/MC (1:99), PMMA/MC (3:97), and PMMA/MC (5:95) films display a dense morphological structure similar to the MC film. The reason for this phenomenon is that (1) when the MC content is low (e.g., PMMA/MC (9:1) and PMMA/MC (7:3) films), PMMA agglomerates significantly and generates remarkable phase separation, consequently, causing many voids in the films; (2) as the MC content increases (PMMA content decreases) (e.g., PMMA/MC (1:1), PMMA/MC (3:7), and PMMA/MC (1:9) films), PMMA molecules can agglomerate into a spherical shape because of the poor compatibility of MC and PMMA; and (3) with a further increase in the MC content (e.g., PMMA/MC (5:95), PMMA/MC (3:97), and PMMA/MC (1:99) films), MC is homogeneously hybridized with PMMA, and hence there is no agglomerated PMMA, leading to a dense morphological structure.

Mechanical Properties. The dependent relationship of mechanical properties (tensile strength and breaking elongation) of PMMA/MC films with the PMMA/MC mass ratio $(R_{PMMA/MC})$ is shown in Figures 2 and 3. Because neat PMMA is too fragile to form films, its mechanical properties are not determined. Strikingly, the hybridization of PMMA with MC considerably improved the tensile strength of the PMMA/MC film (Figure 2). Moreover, the tensile strength dramatically increases with the increase of MC content in the film and reaches a maximum value at $R_{MC/PMMA} = 97:3$. For example, the tensile strengths of the PMMA/MC (3:97) and PMMA/MC (1:1) films are higher than that of the PMMA/MC (9:1) film by about 471 and 83%, respectively. Moreover, it is interesting to find that the tensile strengths of the PMMA/MC (3:7) (19.9 MPa), PMMA/MC (1:9) (30.0 MPa), PMMA/MC (5:95) (34.9 MPa), PMMA/MC (3:97) (40.1 MPa), and PMMA/MC (1:99) (35.8 MPa) films are almost 1.2 times, 1.7 times, 2.0 times, 2.3 times, and 2.1 times that of the printing paper (17.2 MPa), respectively. Similar to the tensile strengths, the elongations at break of the films are significantly enhanced because of the hybridization of PMMA with MC (Figure 3). These findings indicate that the composite of PMMA with MC can significantly enhance not only the tensile strength but also the flexibility of the film. This is mainly ascribed to the excellent film-making capability and strong mechanical properties of MC.

Influence of Thermal Compression on Mechanical Properties. The PMMA/MC (3:97) and PMMA/MC (1:1) films are selected as representatives to examine the influence of
thermal compression on mechanical properties. The tensile strengths and elongations at break before and after thermal compression are shown in Figures 4 and 5, respectively. As seen in Figure 4, thermal compression can improve the tensile strength. For example, the tensile strength of the PMMA/MC (3:97) film after thermal compression at 10 MPa and 90 °C is higher than that without thermal compression treatment. A similar trend is also observed for the PMMA/MC (1:1) film. The PMMA/MC (3:97) film was selected to estimate the effect of thermal compression temperature on tensile strength and elongation at break. It was found that at a fixed compression of 10 MPa, the tensile strength increases with the increase of temperature. Consequently, the tensile strength of the PMMA/MC (3:97) film after thermal compression at 90 °C is higher than that after thermal compression at 70 °C. Similarly, the elongation at break of the PMMA/MC (3:97) film also increases with increasing temperature, as shown in Figure 5. Based on the above analysis, it is reasonable to state that thermal compression is favorable to improvements in tensile strength and breaking elongation of the films. This is mainly ascribed to the fact that the thermal compression treatment can effectively reduce interspaces and stress concentration, make the film more compact, and thus increase its tensile strength and breaking elongation.

Mechanical Properties of the Recovered PMMA/MC Film. The recovery and recycling of materials are of great significance for sustainable social development and environmental protection. As such, the PMMA/MC (1:1) composite film, as a model representative, was dissolved in HFIP to obtain the PMMA/MC (1:1)/HFIP solution, then the solution was employed to reprepare the PMMA/MC (1:1) film. Furthermore, the tensile strength and breaking elongation of the reprepared PMMA/MC (1:1) film were estimated. It is found that the recovered PMMA/MC (1:1) film displays almost identical mechanical properties (13.2 MPa tensile strength and 11.2% elongation at break) to the original composite film (12.8 MPa tensile strength and 10.7% breaking elongation). This shows that the PMMA/MC film can be feasibly recovered and reused. This also indicates that the PMMA/MC films can be used as sustainable products and possess great potential as an alternative to petroleum-based polymer film products which are difficult to degrade and bring about environmental issues.

13C NMR Spectroscopy and XRD Analysis. The solid-state 13C NMR spectra of RPMMA (regenerated from 5 wt % of PMMA solution in HFIP), the MC/PMMA (1:1) film and original MC are presented in Figure 6. It can be seen from Figure 6 that the 13C NMR chemical signals of MC and PMMA appear on the 13C NMR spectra of the MC/PMMA (1:1) film. A similar trend is also observed for the PMMA/MC (1:1) film. The PMMA/MC (3:97) film was selected to estimate the effect of thermal compression treatment on tensile strength and elongation at break. It was found that at a fixed compression of 10 MPa, the tensile strength increases with the increase of temperature. Consequently, the tensile strength of the PMMA/MC (3:97) film after thermal compression at 90 °C is higher than that after thermal compression at 70 °C.

| Figure 4. Tensile strengths: (a) PMMA/MC (3:97) film; (b) PMMA/MC (3:97) film after hot compression at 70 °C and 10 MPa; (c) PMMA/MC (3:97) film after hot compression at 90 °C and 10 MPa; (d) PMMA/MC (1:1) film; and (e) PMMA/MC (1:1) film after hot compression at 90 °C and 10 MPa. |
| Figure 5. Breaking elongations: (a) PMMA/MC (3:97) film; (b) PMMA/MC (3:97) film after hot compression at 70 °C and 10 MPa; (c) PMMA/MC (3:97) film after hot compression at 90 °C and 10 MPa; (d) PMMA/MC (1:1) film; and (e) PMMA/MC (1:1) film after hot compression at 90 °C and 10 MPa. |
| Figure 6. Solid-state 13C NMR spectra of original MC, MC/PMMA (1:1) film, and RPMMA. |
amorphous structure with two broad diffraction peaks at around 2θ values of 15 and 30°.7,8 In the XRD patterns of the PMMA/MC films, the diffraction signal for MC at 8.9° is absent, and the intensity of the diffraction signal at 19.7° is decreased. At the same time, the intensity of the diffraction signal at 19.7° for MC becomes weaker with an increase in the amount of PMMA in proportion to MC. Moreover, the two broad diffraction signals for PMMA disappear in the PMMA/MC films. This is indicative of a decrease in the crystallinity of MC and PMMA in PMMA/MC composites after MC is hybridized with PMMA.

### CONCLUSIONS

High-performance films were successfully fabricated from eco-friendly PMMA and MC by a simple procedure at ambient temperatures. The mechanical properties of the PMMA/MC films are dramatically enhanced compared with neat PMMA. Moreover, the mechanical properties of the film could be further improved by thermal compression. More importantly, the films could be reused after recovery, and the recovered composites still possessed good mechanical properties similar to the original film. Because of their higher tensile strengths than the widely used printing paper, PMMA/MC (3:7), PMMA/MC (1:9), PMMA/MC, PMMA/MC, and PMMA/MC (1:99) films are expected to be applied in the packaging material field.

### AUTHOR INFORMATION

**Corresponding Authors**

Airong Xu — School of Chemical Engineering & Pharmaceutics, Henan University of Science and Technology, Luoyang, Henan 471003, P. R. China; orcid.org/0000-0002-6601-9754; Phone: +86-379-64231914; Email: airongxu@haust.edu.cn; Fax: +86-379-64231914

Rukuan Liu — State Key Laboratory of Utilization of Woody Oil Resource, Hunan Academy of Forestry, Changsha, Hunan 410004, P. R. China; Email: liirukuan@gmail.com

**Authors**

Yongxin Wang — School of Chemical Engineering & Pharmaceutics, Henan University of Science and Technology, Luoyang, Henan 471003, P. R. China

Tongtong Duo — School of Chemical Engineering & Pharmaceutics, Henan University of Science and Technology, Luoyang, Henan 471003, P. R. China

Xingmin Xu — School of Forensic Medicine, Henan University of Science and Technology, Luoyang, Henan 471003, P. R. China

Zhihong Xiao — State Key Laboratory of Utilization of Woody Oil Resource, Hunan Academy of Forestry, Changsha, Hunan 410004, P. R. China

Chaobo Jiang — School of Chemical Engineering & Pharmaceutics, Henan University of Science and Technology, Luoyang, Henan 471003, P. R. China

Junning Lu — School of Chemical Engineering & Pharmaceutics, Henan University of Science and Technology, Luoyang, Henan 471003, P. R. China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c02249

**Notes**

The authors declare no competing financial interest.

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### REFERENCES

1. Bafna, M.; Kumar Gupta, A.; Khanna, R. K. Effect of Potassium Chromate Nanoparticles on the Optical Properties of Poly (Methyl Methacrylate) (PMMA) Films. Mater. Today: Proc. 2019, 10, 38–45.
2. Chen, C.; Li, D.; Hu, Q.; Wang, R. Properties of Polymethyl Methacrylate-Based Nanocomposites: Reinforced with Ultra-Long Chitin Nanofibrer Extracted from Crab Shells. Mater. Des. 2014, 56, 1049–1056.
3. Tihan, T. G.; Ionita, M. D.; Popescu, R. G.; Iordachescu, D. Effect of Hydrophilic-Hydrophobic Balance on Biocompatibility of Poly(Methyl Methacrylate)-(PMMA)-Hydroxyapatite (HA) Composites. Mater. Chem. Phys. 2009, 118, 265–269.
4. Kowalonek, J.; Kaczmarek, H.; Kurzawa, M. Effect of UV-Irradiation on Fluorescence of Poly(Methyl Methacrylate) Films with Photosensitive Organic Compounds. J. Photochem. Photobiol., A 2016, 319–320, 18–24.
5. Mahant, Y. P.; Kondawar, S. B.; Bhute, M.; Nandanwar, D. V. Electrospray Poly (Vinylidene Fluoride)/Poly (Methyl Methacrylate) Composite Nanofibers Polymer Electrolyte for Batteries. Proc. Mater. Sci. 2015, 10, 595–602.
6. Tomar, A. K.; Mahendra, S.; Chahal, R. P.; Kumar, S. Structural and Dielectric Spectroscopic Studies of Poly(aniline–Poly(Methyl Methacrylate)) Composite Films. Synth. Met. 2012, 162, 820–826.
7. Ho, H.; Kim, J. Fabrication of Poly(methyl Methacrylate) Composites with Silanized Boron Nitride by In-Situ Polymerization for High Thermal Conductivity. Compos. Sci. Technol. 2019, 172, 153–162.
8. Lin, W.; Ni, Y.; Pang, J. Microfluidic Spinning of Poly (Methyl Methacrylate)/Konjac Glucomannan Active Food Packaging Films Based on Hydrophilic/Hydrophobic Strategy. Carbohydr. Polym. 2019, 222, 114986.
9. Davijani, A. A. B.; Chang, H.; Liu, H. C.; Luo, J.; Kumar, S. Stress Transfer in Nanocomposites Enabled by Poly (Methyl Methacrylate) Wrapping of Carbon Nanotubes. Polymer 2017, 130, 191.
(10) Ni, X.; Cheng, W.; Huan, S.; Wang, D.; Han, G. Electrospun Cellulose Nanocrystals/Polymethyl Methacrylate) Composite Nanofibers: Morphology, Thermal and Mechanical Properties. Carbohydr. Polym. 2019, 206, 29–37.

(11) Wang, W.; Liang, T.; Zhang, B.; Bai, H.; Ma, P.; Dong, W. Green Functionalization of Cellulose Nanocrystals for Application in Reinforced Polymethyl Methacrylate Nanocomposites. Carbohydr. Polym. 2018, 202, 591–599.

(12) Hui, W.; Zhou, Y.; Dong, Y.; Cao, Z.-J.; He, F.-Q.; Cai, M.-Z.; Tao, D.-J. Efficient Hydrolysis of Hemicellulose to Furfural by Novel Superacid SO4h-Functionalized Ionic Liquids. Green Energy Environ. 2019, 4, 49–55.

(13) An, X.-C.; Li, Z.-M.; Zhou, Y.; Zhu, W.; Tao, D.-J. Rapid Capture and Efficient Removal of Low-Concentration SO2 in Simulated Flue Gas by Hypercrosslinked Hollow Nanotube Ionic Polymers. Chem. Eng. J. 2020, 394, 124859.

(14) Chen, F.-F.; Huang, K.; Fan, J.-P.; Tao, D.-J. Chemical Solvent in Chemical Solvent: A Class of Hybrid Materials for Effective Capture of CO2. AIChE J. 2018, 64, 632–639.

(15) Tao, D.-J.; Chen, F.-F.; Tian, Z.-Q.; Huang, K.; Mahurin, S. M.; Jiang, D.-e.; Dai, S. Highly Efficient Carbon Monoxide Capture by Carbon-functionalized Ionic Liquids through C-Site Interactions. Angew. Chem., Int. Ed. 2017, 56, 6843–6847.

(16) Matta, E.; Tavern Quiroz, M. J.; Bertola, N. Active Edible Films of Methylcellulose with Extracts of Green Apple (Granny Smith) Skin. Int. J. Biol. Macromol. 2019, 124, 1292–1298.

(17) Khan, R. A.; Salmieri, S.; Dussault, D.; Uribe-Calderon, J.; Kamal, M. R.; Safra ny, A.; Lacroix, M. Production and Properties of Nanocellulose-reinforced Methylcellulose-based Biodegradable Films. J. Agric. Food Chem. 2010, 58, 7878–7885.

(18) Bounail, A.; Salmieri, S.; Klimas, E.; Tawema, P. O.; Bouchard, J.; Lacroix, M. Characterization of Trilayer Antimicrobial Diffusion Films (ADFS) Based on Methylcellulose-Polycaprolactone Composites. J. Agric. Food Chem. 2013, 61, 811–821.

(19) Sun, X.; Chi, Y.; Mu, T. Studies on Staged Precipitation of Cellulose from an Ionic Liquid by Compressed Carbon Dioxide. Green Chem. 2014, 16, 2736–2744.

(20) Das, B.; Basu, A.; Maji, S.; Dutta, K.; Dewan, M.; Adhikary, A.; Maiti, T. K.; Chattopadhyay, D. Nanotailored Hyaluronic Acid Modified Methylcellulose as an Injectable Scaffold with Enhanced Physico-Rheological and Biological Aspects. Carbohydr. Polym. 2020, 237, 116146.

(21) Tan, W.; Zhang, J.; Zhao, X.; Li, Q.; Dong, F.; Guo, Z. Preparation and Phsyicochemical Properties of Antioxidant Chitosan Ascorbate/Methylcellulose Composite Films. Int. J. Biol. Macromol. 2020, 146, 53–61.

(22) Fadeeva, I. V.; Trofimchuk, E. S.; Dedushenko, S. K.; Fomin, A. S.; Davydova, G. A.; Selezneva, I. I.; Perfiliev, Y. D.; Barinov, S. M. Methylcellulose Films Partially Crosslinked by Iron Compounds for Medical Applications. Mater. Today Commun. 2019, 18, 54–59.

(23) Vargas, M.; Albors, A.; Chiralt, A.; Gonzalez-Martinez, C. Water Interactions and Microstructure of Chitosan-Methylcellulose Composite Films as Affected by Ionic Concentration. LWT–Food Sci. Technol. 2011, 44, 2290–2295.

(24) Synytsya, A.; Grafova, M.; Slepicka, P.; Gedeon, O.; Synytsya, A. Modification of Chitosan—Methylcellulose Composite Films with Meso-Tetrakis[4-(Sulfonatophenyl)]Porphyrin. Biomacromolecules 2012, 13, 489–498.

(25) Zuo, M.; Song, Y.; Zheng, Q. Preparation and Properties of Wheat Gluten/Methylcellulose Binary Blend Film Casting from Aqueous Ammonia: A Comparison with Compression Molded Composites. J. Food Eng. 2009, 91, 415–422.

(26) Gupta, A.; Khatyay, V. Cellulose Functionalized High Molecular Weight Stereocomplex Polylactic Acid Biocomposite Films with Improved Gas Barrier, Thermomechanical Properties. ACS Sustainable Chem. Eng. 2017, 5, 6835–6844.

(27) Al-Tayyar, N. A.; Youssef, A. M.; Al-hindi, R. Antimicrobial Food Packaging Based on Sustainable Bio-Based Materials for Reducing Foodborne Pathogens: A Review. Food Chem. 2020, 310, 125915.