PVC-SiO₂-Ag composite as a powerful biocide and anti-SARS-CoV-2 material

Marcelo Assis^{1,2} · Luiz Gustavo P. Simoes³ · Guilherme C. Tremiliosi³ · Lara Kelly Ribeiro¹ · Dyovani Coelho¹ · Daniel T. Minozzi³ · Renato I. Santos³ · Daiane C. B. Vilela³ · Lucia Helena Mascaro¹ · Juan Andrés² · Elson Longo¹

Received: 31 May 2021 / Accepted: 23 August 2021 / Published online: 31 August 2021
© The Polymer Society, Taipei 2021

Abstract

The ongoing COVID-19 pandemic has pushed scientists and technologists to find novel strategies to develop new materials to prevent the transmission, spread, and entry of pathogens into the human body. In this report, the fabrication of polyvinyl chloride (PVC)-SiO₂-Ag composite is presented, in which the percentage of Ag is 0.84% wt. Our findings render that this composite eliminates (> 99.8%) bacteria and fungus (*Staphylococcus aureus*, *Escherichia coli*, *Penicillium funiculosum*) and SARS-CoV-2, by surface contact in 2 h hours and 15 min, respectively. Specific migration analysis shown that the use of the PVC-SiO₂-Ag composite is considered safe and effective for food preservation. This research and innovation front can be considered a breakthrough for the design of biocide materials. Future directions for this exciting and highly significant research field can open the door to the development of new technologies for the fabrication of packaging films to protect consumer products (such as fruits, vegetables, and other foods).

Keywords PVC-SiO₂-Ag composite · Biocide composite · Anti-SARS-CoV-2 material · PVC

Introduction

Currently, microorganisms (including bacteria, fungi and viruses) are one of the main causes of disease in the world [1]. The public health outbreaks caused by emerging COVID-19 infectious diseases constitute the forefront of current global safety concerns and a significant burden on global economies [2–4]. While there is an urgent need for the effective treatment of these outbreaks based on antiviral and vaccines, it is essential to explore any other effective intervention strategies that may reduce the mortality and morbidity rates of the disease [5, 6]. The development of innovative materials able to prevent the transmission, spread, and entry of COVID-19 pathogens into the human body is currently in the spotlight. The synthesis of these materials

is, therefore, gaining momentum, as methods are providing nontoxic and environmentally acceptable “green chemistry” procedures [7].

It has been known for over a century that silver nanoparticles (Ag NPs) are one of the most active against microorganisms and they are widely used due to their antiviral properties and the lower chance of developing resistance when compared to conventional antivirals [8–10]. Ag NPs present excellent bio-activities and have been incorporated into a wide variety of consumer products including protective equipment, clothing, food containers, packaging, and air purifiers (Project on Emerging Nanotechnologies) [11]. Nevertheless, Ag NPs are reactive and unstable in physiological conditions, and their practical applications are often hampered by oxidization, which results in aggregation and the loss of antimicrobial activity [12]. To solve this problem, Ag NPs can be dispersed on metal oxides to form metal/semiconductor composites, which are employed with success in a wide range of applications, including heterogeneous catalysis, energy conversion and environmental applications [13].

Ag NPs display a unique characteristic associated with the localized surface plasmon resonance (SPR) behavior [14, 15], which render remarkable antimicrobial activity [16–18]. This is mainly due to the following factors: (i) the SPR

✉ Juan Andrés
andres@qfa.uji.es

¹ CDMF, LIEC, Federal University of São Carlos - (UFSCar), São Carlos, SP 13565-905, Brazil

² Department of Physical and Analytical Chemistry, University Jaume I (UJI), 12071 Castellon, Spain

³ Nanox Tecnologia S/A, São Carlos, SP 13562-400, Brazil

adsorption and high electron trapping ability of Ag NPs are beneficial for promoting solar energy conversion [19, 20], water splitting [21, 22], photocatalytic [23–25] and antimicrobial [26–29] activities of the composites, (ii) the excellent conductivity of Ag NPs at the interface improve the transfer of charges from SPR metals to semiconductors, thus leading to enhanced activity [30]. Previously, we demonstrated an anti-SARS-CoV-2 activity, which efficiently hampered infection and transmission via surfaces; in particular, an antimicrobial coating, a polycotton fiber Ag based material, that could rapidly kill bacteria *Staphylococcus aureus* (*S. aureus*), *Escherichia coli* (*E. coli*), fungi (*Candida albicans*), and SARS-CoV-2 by contact was presented [31].

The amorphous semiconductor SiO₂ meets many important requirements, i.e. ease of synthesis and low cost, high biocompatibility and biodegradability, hydrophilicity, stability, optical transparency tunable size, and versatile surface chemistry [32, 33]. Due to its unique characteristics, it has been employed in a wide range of applications, such as cosmetics, food, pharmaceuticals and medicine [34, 35]. Taking advantage of SiO₂ as an efficient host for stabilizing Ag NPs and the SiO₂-Ag heterojunction has attracted considerable attention due to its excellent properties [36–38], in the following study by our research group, Ag NPs were stabilized with semiconductor amorphous SiO₂ to form a SiO₂-Ag heterojunction. This heterojunction was immobilized in a

polymeric matrix (ethyl vinyl acetate), to render a highly virucide material [31]. In this study, we also confirmed, by using scavenger experiments, that hole (h⁺), hydroxyl radical (•OH), and hydroperoxyl radical (•O₂H) are the reactive species along the mechanism of the virus elimination process [31]. It is assumed that the formation and separation of electrons, e⁻, and h⁺, are enhanced due to the synergistic interaction/effect generated at the surface of the SiO₂ semiconductor and the SPR of the Ag NPs at the interface. In the semiconductor, the h⁺, at the valence band, reacts with H₂O by decomposing it into •OH and a proton (H⁺). The e⁻ migrates to the conduction band reacting with O₂ to form a superoxide radical (•O₂⁻), which in turn interacts with H⁺ forming the radical •O₂H. These free radicals are capable of killing microorganisms by oxidizing and breaking down the cell walls and membranes of bacteria, fungi, and viruses, as demonstrated in different heterojunctions formed by Ag NPs and binary and ternary metal oxides [31].

The experimental results indicated that the as-fabricated samples exhibited high antibacterial activity towards *E. coli* and *S. aureus* as well as towards SARS-CoV-2 [31]. Furthermore, this activity can be functionalized as a new technology in the manufacture of medical devices, such as reusable masks and pharmaceutical packaging, food storage packaging materials, displaying high flexibility, biostability and easy processing [39–41]. Emerging foodborne pathogens

Fig. 1 A-B) TEM images of SiO₂-Ag heterojunction. C) Chemical composition from EDS analysis of the sample (weight %)

are considered a major public health and sanitary control, in addition to affecting food processing industries as well as consumers. The consumption of food contaminated by microorganisms leads to different types of foodborne illnesses, an example is the old chain associated with the re-emerging outbreaks of COVID-19 in Beijing, China [42, 43]. Furthermore, countless cases of diseases that are associated with foodborne pathogens are reported every year worldwide [44]. Biocide materials covered by polymers is an important strategy to be applied for different uses, what makes the studies of possible food storage packaging viable and promising because they can inhibit the growth of microorganisms and food spoilage, extending the product a longer shelf life [45, 46].

Inspired by these pioneering studies, in this communication we develop a greener and convenient approach for the synthesis of polyvinyl chloride (PVC)-SiO₂-Ag. PVC is one of the most used thermoplastic polymers worldwide, due to its versatility, high stability and resistance. As a hard thermoplastic it can be used in the packaging of consumer products and for biomedical applications, especially for surgical and dialysis technologies [47]. The PVC-SiO₂-Ag composite proposed in this study has the ability to kill bacteria (*S. aureus*, and *E. coli*), fungus (*Penicillium funiculosum* (*P. funiculosum*)) and SARS-CoV-2 by surface contact. These results demonstrate that this material constitutes an effective platform for simultaneously eliminating different pathogens, avoiding their transmission, protecting packaging of consumer products and increasing the shelf life of perishable foods.

Materials and methods

Experimental details on the method for obtaining the polymeric composite, microbicidal tests and specific migration tests can be found in the Supplementary Material.

Results and discussion

Figure 1A-B shows the transmission electron microscopy (TEM) and energy-dispersive x-ray spectroscopy (EDS) analysis of the SiO₂ microstructures, composed of small, and dark nanoparticles deposited on their surface. The synthesis of the SiO₂-Ag heterojunction and the PVC-SiO₂-Ag composite are shown in the Supplementary Material. When performing the EDS analysis (Fig. 1C) of this region, a ratio of almost 2:1 is observed from O (69.33%) to Si (29.83%), expected for the structure of SiO₂, in addition to a small percentage of Ag (0.84% wt) can be sensed. These results confirm that SiO₂-Ag heterojunction is obtained successfully. The stability of Ag NPs was analyzed by spectrophotometry

in the UV–Vis region, as they are prone to oxidation when dried at high temperatures. There were no differences in the plasmonic absorption band of Ag NPs (573 nm) between samples (heat-treated and not heat-treated), showing that the drying process does not alter the Ag NPs (see Fig. S1 in the Supplementary Material).

Once the composite was obtained, microbiological elimination tests were performed to assess the activity of the material against infectious pathogens. This analysis is the first step to confirm the use of this material in packaging films to protect consumer products, since indirect infections can occur due to contact with contaminated surfaces [48, 49]. These infections occur because pathogenic microorganisms can remain active for long periods on different surfaces, depending on the chemical composition

Fig. 2 (A) Microbicidal results against *S. aureus*, *E. coli* and *P. funiculosum* after 24 h of exposure to pure PVC and PVC-SiO₂-Ag composite. (B) Virucidal results against SARS-CoV-2 using PVC-SiO₂-Ag composite

Table 1 Specific migration for Ag in PVC-SiO₂-Ag composite

Food Simulants	Ag content (µg/Kg)
Olive Oil	< 30 ± 0.0
Ethanol 50%	< 6 ± 0.0
Acetic Acid 3%	11 ± 1.8

while ethanol and olive oil allows us to investigate alcoholic/dairy and fatty foods, respectively [52, 53]. The specific migration analysis shown that for all cases, the Ag content was less than 30 µg/Kg, a mass much smaller than accepted by Commission Regulation, which allows limits below 500 µg/Kg for metals. The specific migration of SiO₂ was not taken into account, as it is not restricted by Commission Regulation [51]. Therefore, the use of the PVC-SiO₂-Ag composite is considered safe and effective for food preservation.

Conclusions

Finding new materials to eliminate microorganisms is clearly a high priority with the emergence of the present COVID-19 pandemic. In this study, we evaluated the efficiency of the PVC-SiO₂-Ag composite and present findings render that this material eliminates bacteria (*S. aureus*, *E. coli*), fungus (*P. funiculosus*), and SARS-CoV-2, by surface contact. Consequently, there is no doubt that materials incorporating this composite in every-day devices such as smartphones clothing, eye- and face-ware like glasses and masks constitutes will be the bases of the development of new technologies for viral disinfection in the sectors of health, processing, storage, and food transportation. In rapidly expanding bioengineering branches, this work contributes to further research to provide comfort and confidence to humans worldwide, by preventing the transmission and contamination of SARS-CoV-2 and other pathogens, and its impacts on society.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1007/s10965-021-02729-1>.

Acknowledgements This work was funded in part by Fundação de Amparo à Pesquisa do Estado de São Paulo—FAPESP, Financiadora de Estudos e Projetos—FINEP, Conselho Nacional de Desenvolvimento Científico e Tecnológico—CNPq, and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES. J.A. acknowledges Universitat Jaume I, and the Ministerio de Ciencia, Innovación y Universidades (Spain) for financially supporting this research.

Authors' contributions M.A.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization. L.K.R.; D.C.: Methodology, Validation, Formal analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing. L.G.P.S.; G.C.T.; D.T.M.; R.I.S.; D.C.B.V.: Resources, Conceptualization, Methodology, Validation, Formal analysis, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization, Funding acquisition. L.H.M.; J.A.; E.L.: Resources, Conceptualization, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization, Funding acquisition.

Funding Fundação de Amparo à Pesquisa do Estado de São Paulo—FAPESP (FAPESP CEPID-finance code 2013/07296-2, FAPESP/SHELL- finance code 2017/11986-5 and PIPE-finance codes 15/50113-3 and 11/51084-4). Financiadora de Estudos e Projetos—FINEP (finance code 03/2013 Ref. 0555/13).

Conselho Nacional de Desenvolvimento Científico e Tecnológico—CNPq (finance code 166,281/2017-4). Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—CAPES (finance code 001).

Universitat Jaume I (project UJI-B2019-30). Ministerio de Ciencia, Innovación y Universidades (Spain) (project PGC2018094417-B-I00).

Availability of data and material The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability Not applicable.

Declarations

Conflicts of interest The authors declare no conflict of interest.

References

1. Steffan JJ, Derby JA, Brevik EC (2020) Soil pathogens that may potentially cause pandemics, including severe acute respiratory syndrome (SARS) coronaviruses. *Curr Opin Environ Sci Heal* 17:35–40. <https://doi.org/10.1016/j.coesh.2020.08.005>
2. Balkhair AA (2020) COVID-19 Pandemic: A New Chapter in the History of Infectious Diseases. *Oman Med J* 35:e123–e123. <https://doi.org/10.5001/omj.2020.41>
3. Arshad Ali S, Baloch M, Ahmed N, Arshad Ali A, Iqbal A (2020) The outbreak of Coronavirus Disease 2019 (COVID-19)—An emerging global health threat. *J Infect Public Health* 13:644–646. <https://doi.org/10.1016/j.jiph.2020.02.033>
4. Shadmi E, Chen Y, Dourado I, Faran-Perach I, Furler J, Hangoma P et al (2020) Health equity and COVID-19: global perspectives. *Int J Equity Health* 19:104. <https://doi.org/10.1186/s12939-020-01218-z>
5. Behrouzi B, Araujo Campoverde MV, Liang K, Talbot HK, Bogoch II, McGeer A et al (2020) Influenza Vaccination to Reduce Cardiovascular Morbidity and Mortality in Patients With COVID-19: JACC State-of-the-Art Review. *J Am Coll Cardiol* 76:1777–1794. <https://doi.org/10.1016/j.jacc.2020.08.028>
6. Paltiel AD, Schwartz JL, Zheng A, Walensky RP (2021) Clinical outcomes of a COVID-19 vaccine: Implementation over efficacy. *Health Aff* 40:42–52. <https://doi.org/10.1377/hlthaff.2020.02054>

7. Ghaffari M, Mollazadeh-Bajestani M, Moztarzadeh F, Uludağ H, Hardy JG, Mozafari M (2021) An overview of the use of biomaterials, nanotechnology, and stem cells for detection and treatment of COVID-19: towards a framework to address future global pandemics. *Emergent Mater* 4:19–34. <https://doi.org/10.1007/s42247-020-00143-9>
8. Sharma VK, Yngard RA, Lin Y (2009) Silver nanoparticles: Green synthesis and their antimicrobial activities. *Adv Colloid Interface Sci* 145:83–96. <https://doi.org/10.1016/j.cis.2008.09.002>
9. Gherasim O, Puiu RA, Bîrcă AC, Burduşel A-C, Grumezescu AM (2020) An Updated Review on Silver Nanoparticles in Biomedicine. *Nanomaterials* 10:2318. <https://doi.org/10.3390/nano10112318>
10. Chernousova S, Eppl M (2013) Silver as Antibacterial Agent: Ion, Nanoparticle, and Metal. *Angew Chemie Int Ed* 52:1636–1653. <https://doi.org/10.1002/anie.201205923>
11. Vance ME, Kuiken T, Vejerano EP, McGinnis SP, Hochella MF, Hull DR (2015) Nanotechnology in the real world: Redeveloping the nanomaterial consumer products inventory. *Beilstein J Nanotechnol* 6:1769–1780. <https://doi.org/10.3762/bjnano.6.181>
12. Syafiuddin A, Salmiati, Salim MR, Beng Hong Kueh A, Hadibarata T, Nur H (2017) A Review of Silver Nanoparticles: Research Trends, Global Consumption, Synthesis, Properties, and Future Challenges. *J Chinese Chem Soc* 64:732–56. <https://doi.org/10.1002/jccs.201700067>
13. Patnaik S, Sahoo DP, Parida K (2018) An overview on Ag modified g-C₃N₄ based nanostructured materials for energy and environmental applications. *Renew Sustain Energy Rev* 82:1297–1312. <https://doi.org/10.1016/j.rser.2017.09.026>
14. Zhou X, Liu G, Yu J, Fan W (2012) Surface plasmon resonance-mediated photocatalysis by noble metal-based composites under visible light. *J Mater Chem* 22:21337–21354. <https://doi.org/10.1039/c2jm31902k>
15. Brongersma ML, Halas NJ, Nordlander P (2015) Plasmon-induced hot carrier science and technology. *Nat Nanotechnol* 10:25–34. <https://doi.org/10.1038/nnano.2014.311>
16. Wady AF, Machado AL, Foggi CC, Zamperini CA, Zucolotto V, Moffa EB et al (2014) Effect of a Silver Nanoparticles Solution on *Staphylococcus aureus* and *Candida* spp. *J Nanomater* 2014:1–7. <https://doi.org/10.1155/2014/545279>
17. Zheng K, Setyawati MI, Leong DT, Xie J (2018) Antimicrobial silver nanomaterials. *Coord Chem Rev* 357:1–17. <https://doi.org/10.1016/j.ccr.2017.11.019>
18. Moneris M, Broglia MF, Yslas EI, Barbero CA, Rivarola CR (2019) Highly effective antimicrobial nanocomposites based on hydrogel matrix and silver nanoparticles: Long-lasting bactericidal and bacteriostatic effects. *Soft Matter* 15:8059–8066. <https://doi.org/10.1039/c9sm01118h>
19. Rho W-Y, Chun M-H, Kim H-S, Kim H-M, Suh J, Jun B-H (2016) Ag Nanoparticle-Functionalized Open-Ended Freestanding TiO₂ Nanotube Arrays with a Scattering Layer for Improved Energy Conversion Efficiency in Dye-Sensitized Solar Cells. *Nanomaterials* 6:117. <https://doi.org/10.3390/nano6060117>
20. Cushing SK, Bristow AD, Wu N (2015) Theoretical maximum efficiency of solar energy conversion in plasmonic metal–semiconductor heterojunctions. *Phys Chem Chem Phys* 17:30013–30022. <https://doi.org/10.1039/C5CP04512F>
21. Yu J, Zhang L, Qian J, Zhu Z, Ni S, Liu G et al (2019) In situ exsolution of silver nanoparticles on AgTaO₃-SrTiO₃ solid solutions as efficient plasmonic photocatalysts for water splitting. *Appl Catal B Environ* 256:117818. <https://doi.org/10.1016/j.apcatb.2019.117818>
22. Ingram DB, Linic S (2011) Water Splitting on Composite Plasmonic-Metal/Semiconductor Photoelectrodes: Evidence for Selective Plasmon-Induced Formation of Charge Carriers near the Semiconductor Surface. *J Am Chem Soc* 133:5202–5205. <https://doi.org/10.1021/ja200086g>
23. Liu T, Li B, Hao Y, Han F, Zhang L, Hu L (2015) A general method to diverse silver/mesoporous–metal–oxide nanocomposites with plasmon-enhanced photocatalytic activity. *Appl Catal B Environ* 165:378–88. <https://doi.org/10.1016/j.apcatb.2014.10.041>
24. Assis M, Groppo Filho FC, Pimentel DS, Robeldo T, Gouveia AF, Castro TFD et al (2020) Ag Nanoparticles/AgX (X=Cl, Br and I) Composites with Enhanced Photocatalytic Activity and Low Toxicological Effects. *ChemistrySelect* 5:4655–73. <https://doi.org/10.1002/slct.202000502>
25. Chen K-H, Pu Y-C, Chang K-D, Liang Y-F, Liu C-M, Yeh J-W et al (2012) Ag-Nanoparticle-Decorated SiO₂ Nanospheres Exhibiting Remarkable Plasmon-Mediated Photocatalytic Properties. *J Phys Chem C* 116:19039–19045. <https://doi.org/10.1021/jp306555j>
26. Assis M, Cordoncillo E, Torres-Mendieta R, Beltrán-Mir H, Mínguez-Vega G, Oliveira R et al (2018) Towards the scale-up of the formation of nanoparticles on α -Ag₂WO₄ with bactericidal properties by femtosecond laser irradiation. *Sci Rep* 8:1884. <https://doi.org/10.1038/s41598-018-19270-9>
27. Macedo NG, Machado TR, Roca RA, Assis M, Foggi CC, Puerto-Belda V et al (2019) Tailoring the Bactericidal Activity of Ag Nanoparticles/ α -Ag₂WO₄ Composite Induced by Electron Beam and Femtosecond Laser Irradiation: Integration of Experiment and Computational Modeling. *ACS Appl Bio Mater* 2:824–837. <https://doi.org/10.1021/acsabm.8b00673>
28. D’Lima L, Phadke M, Ashok VD (2020) Biogenic silver and silver oxide hybrid nanoparticles: a potential antimicrobial against multi drug-resistant *Pseudomonas aeruginosa*. *New J Chem* 44:4935–4941. <https://doi.org/10.1039/C9NJ04216D>
29. Assis M, Robeldo T, Foggi CC, Kubo AM, Mínguez-Vega G, Condoncillo E et al (2019) Ag Nanoparticles/ α -Ag₂WO₄ Composite Formed by Electron Beam and Femtosecond Irradiation as Potent Antifungal and Antitumor Agents. *Sci Rep* 9:9927. <https://doi.org/10.1038/s41598-019-46159-y>
30. Joseph CG, Taufiq-Yap YH, Musta B, Sarjadi MS, Elilarasi L (2021) Application of Plasmonic Metal Nanoparticles in TiO₂-SiO₂ Composite as an Efficient Solar-Activated Photocatalyst: A Review Paper. *Front Chem* 8:1283. <https://doi.org/10.3389/fchem.2020.568063>
31. Assis M, Simoes LGP, Tremiliosi GC, Coelho D, Minozzi DT, Santos RI et al (2021) SiO₂-Ag Composite as a Highly Virucidal Material: A Roadmap that Rapidly Eliminates SARS-CoV-2. *Nanomaterials* 11:638. <https://doi.org/10.3390/nano11030638>
32. Colilla M, Vallet-Regí M (2020) Targeted Stimuli-Responsive Mesoporous Silica Nanoparticles for Bacterial Infection Treatment. *Int J Mol Sci* 21:8605. <https://doi.org/10.3390/ijms21228605>
33. Kesse S, Boakye-Yiadom K, Ochete B, Opoku-Damoah Y, Akhtar F, Filli M et al (2019) Mesoporous Silica Nanomaterials: Versatile Nanocarriers for Cancer Theranostics and Drug and Gene Delivery. *Pharmaceutics* 11:77. <https://doi.org/10.3390/pharmaceutics11020077>
34. Ahsani M, Hazrati H, Javadi M, Ulbricht M, Yegani R (2020) Preparation of antibiofouling nanocomposite PVDF/Ag-SiO₂ membrane and long-term performance evaluation in the MBR system fed by real pharmaceutical wastewater. *Sep Purif Technol* 249:116938. <https://doi.org/10.1016/j.seppur.2020.116938>
35. Sriramulu D, Reed EL, Annamalai M, Venkatesan TV, Valiyaveetil S (2016) Synthesis and Characterization of Superhydrophobic. Self-cleaning NIR-reflective Silica Nanoparticles *Sci Rep* 6:35993. <https://doi.org/10.1038/srep35993>
36. Zhou Y, Wang L, Zhang H, Bai Y, Niu Y, Wang H (2012) Enhanced high thermal conductivity and low permittivity of polyimide based composites by core-shell Ag@SiO₂ nanoparticle fillers. *Appl Phys Lett* 101:012903. <https://doi.org/10.1063/1.4733324>
37. Liu J, Li S, Fang Y, Zhu Z (2019) Boosting antibacterial activity with mesoporous silica nanoparticles supported silver

- nanoclusters. *J Colloid Interface Sci* 555:470–479. <https://doi.org/10.1016/j.jcis.2019.08.009>
38. Abduraimova A, Molkenova A, Duisembekova A, Mulikova T, Kanayeva D, Atabaev TS (2021) Cetyltrimethylammonium Bromide (CTAB)-Loaded SiO₂-Ag Mesoporous Nanocomposite as an Efficient Antibacterial Agent. *Nanomaterials* 11:477. <https://doi.org/10.3390/nano11020477>
 39. Osman AF, Alakrach AM, Kalo H, Azmi WNW, Hashim F (2015) In vitro biostability and biocompatibility of ethyl vinyl acetate (EVA) nanocomposites for biomedical applications. *RSC Adv* 5:31485–31495. <https://doi.org/10.1039/C4RA15116J>
 40. Ma Y, Li J, Si Y, Huang K, Nitin N, Sun G (2019) Rechargeable Antibacterial N-Halamine Films with Antifouling Function for Food Packaging Applications. *ACS Appl Mater Interfaces* 11:17814–17822. <https://doi.org/10.1021/acsami.9b03464>
 41. Omerović N, Djisalov M, Živojević K, Mladenović M, Vunduk J, Milenković I et al (2021) Antimicrobial nanoparticles and biodegradable polymer composites for active food packaging applications. *Compr Rev Food Sci Food Saf* 20:2428–54. <https://doi.org/10.1111/1541-4337.12727>
 42. Pang X, Ren L, Wu S, Ma W, Yang J, Di L et al (2020) Cold-chain food contamination as the possible origin of COVID-19 resurgence in Beijing. *Natl Sci Rev* 7:1861–1864. <https://doi.org/10.1093/nsr/nwaa264>
 43. Han J, Zhang X, He S, Jia P (2021) Can the coronavirus disease be transmitted from food? A review of evidence, risks, policies and knowledge gaps. *Environ Chem Lett* 19:5–16. <https://doi.org/10.1007/s10311-020-01101-x>
 44. Bintsis T (2017) Foodborne pathogens *AIMS Microbiol* 3:529–563. <https://doi.org/10.3934/microbiol.2017.3.529>
 45. Parra DF, Marchini LG, Komatsu LGH, de Oliveira CB, Oliani WL, Rangari VK (2021) AgNPs@ZnO hybride nanoparticles infused thermoplastic polyester elastomer and their biocide effect. *SN Appl Sci* 3:1–13. <https://doi.org/10.1007/s42452-021-04365-2>
 46. Arumugam M, Murugesan B, Pandiyan N, Chinnalagu DK, Rangasamy G, Mahalingam S (2021) Electrospinning cellulose acetate/silk fibroin/Au-Ag hybrid composite nanofiber for enhanced biocidal activity against MCF-7 breast cancer cell. *Mater Sci Eng C* 123:112019
 47. Ebnalwaleed AA, Thabet A (2016) Controlling the optical constants of PVC nanocomposite films for optoelectronic applications. *Synth Met* 220:374–83. <https://doi.org/10.1016/j.synthmet.2016.07.006>
 48. Khaiboullina S, Uppal T, Dhabarde N, Subramanian VR, Verma SC (2020) Inactivation of Human Coronavirus by Titania Nanoparticle Coatings and UVC Radiation: Throwing Light on SARS-CoV-2. *Viruses* 13:19. <https://doi.org/10.3390/v13010019>
 49. Marquès M, Domingo JL (2021) Contamination of inert surfaces by SARS-CoV-2: Persistence, stability and infectivity. A review *Environ Res* 193:110559. <https://doi.org/10.1016/j.envres.2020.110559>
 50. Kusumaningrum HD, Riboldi G, Hazeleger WC, Beumer RR (2003) Survival of foodborne pathogens on stainless steel surfaces and cross-contamination to foods. *Int J Food Microbiol* 85:227–236. [https://doi.org/10.1016/S0168-1605\(02\)00540-8](https://doi.org/10.1016/S0168-1605(02)00540-8)
 51. Commission regulation (2011) (EU) No 10, 2011 of 14, January 2011 on plastic materials and articles intended to come into contact with food. *Off J Eur Community* 12
 52. Alnafouri AJ, Franz R (1999) A study on the equivalence of olive oil and the EU official substitute test media for migration testing at high temperatures. *Food Addit Contam* 16:419–431. <https://doi.org/10.1080/026520399283812>
 53. Cooper I, Goodson A, O'Brien A (1998) Specific migration testing with alternative fatty food simulants. *Food Addit Contam* 15:72–78. <https://doi.org/10.1080/02652039809374600>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.