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Given the unprecedented challenges posed by the COVID-19 epidemic, and delayed response from a biosafety standpoint to contain the spread, the society. Most outbreaks have been due to poor biosafety standards, which has provided a setback to the global economy while severely impacting human society and the environment [1]. Be it the Spanish Flu, H1N1 Swine Flu, Ebola outbreak, the Zika virus or COVID-19, each pandemic has exposed huge gaps in the healthcare industry that include lack of effective vaccines and medicines, testing of infection, real-time monitoring of the spread of the virus, inadequate protective equipment, and scarcity of protective and intensive care of patients. Some of these may be attributed to a lack of focused research in biosafety materials. As a consequence of the pandemic, a significant body of research activities has therefore focused on biosafety materials that possess unique properties needed for biosafety applications. This graphical review aims to provide a perspective on the usage of bio-based materials to handle the imposing challenges in biosafety. This review investigates existing developments in bio-based antimicrobial encapsulations as an effective measure to deter the growth of COVID-19 virus on surfaces and minimize its spread through surface contact. This will help researchers develop further strategies in material science to focus on contagious pathogens in the future.

1. Introduction

Advancements in the field of biotechnology and associated research on finding and developing new pathogens have exposed the gaps in biosafety measures and standards across the globe. This has resulted in the outbreak of infectious diseases globally, posing grave dangers to human society and the environment [1]. Be it the Spanish Flu, H1N1 Swine Flu, Ebola outbreak, the Zika virus or COVID-19, each pandemic has provided a setback to the global economy while severely impacting the society. Most outbreaks have been due to poor biosafety standards and delayed response from a biosafety standpoint to contain the spread. Given the unprecedented challenges posed by the COVID-19 epidemic, there is a resurgence of interest in the biosafety industry that can better prepare the world for similar situations in the future as well as contain the current pandemic. This entails a need to push forward the technologies and techniques in material science [2] which is an integral part of improving the biosafety standards and producing materials that can protect against these potentially deadly pathogens. The development of effective antiviral and antimicrobial coatings and treatments is particularly important in the transport industries like aerospace.

While there have been some commercially available materials that are effective against pathogens [3,4], the unknown nature of COVID-19 virus has resulted in a need to study the impact of other prospective biosafety materials candidates that could prove useful in remediating the...
2. Antimicrobial materials for preventing COVID-19 growth

It has been found that the contamination of a push plate door entrance into an office building can lead to contamination of 50% of the commonly touched surfaces and hands of office workers within 4 h [13]. Microbial growth occurs in public places on the surfaces of common contact areas due to the formation of a biofilm which provides a feasible environment for bacteria to secrete extracellular polymeric substances resulting in the capture of enveloped viruses such as coronaviruses on the surface. COVID-19, being an enveloped virus, has four main structural proteins i.e. spike (S), envelope (E), membrane (M), and nucleocapsid (N) proteins (Fig. 1). The S-protein in COVID-19 attaches itself to various surfaces resulting in its transmission [14].

As reported by Ref. [15] COVID-19 virus can survive for up to 4 h on copper, several hours on aluminium, sterile sponges, or surgical gloves, up to 24 h on cardboard and 2–3 days on plastic and stainless-steel surface. Thus, it is imperative to prevent the spread of COVID-19 on these surfaces through antimicrobial encapsulation that will deter their capture and growth. Surfaces treated with antiviral encapsulations render the viruses non-infective on encountering the treated surface. Nanomaterials have been found to possess antimicrobial impact due to their unique chemical and physical characteristics and high surface-area-to-volume ratio. The nanoparticles facilitate presentation and stabilization of the antigens on administration and further serve as adjuvants for boosting the immune response. They act as carriers for target-based delivery of antigens against viruses. Metal nanoparticles can adhere to the viral envelope, the membrane of cells, and then enter into the interior, destroying genetic materials such as DNA and RNA [16] (Fig. 2).

Ag nanoparticles (AgNP) have received special attention due to their applicability across multiple sectors as an antimicrobial protection layer in air filters, textiles, biomedical industry and food packaging [11]. used orange (Citrus sinensis) waste to extract AgNP which has been proven to be effective against microbes. AgNPs have further prevented the activity of viruses by eliminating aerosolised bacteriophage MS2 virus particles [17]. Invitro studies have observed that AgNPs can inactivate several types of viruses like monkeypox virus, Tacaribe virus, HIV-1, hepatitis B, Rift Valley fever virus, influenza viruses such as H1N1 and H3N2 [18], [19]; encapsulated natural curcumin in a novel polymeric micelle (PM) in presence of AgNP to enhance the antimicrobial activity of the material on Pseudomonas aeruginosa (P. aeruginosa) and Staphylococcus aureus (S. aureus) (Fig. 3).

Nanomaterials are also effective in reducing the in vivo replication of the viruses from various families. Although chitosan already possesses antimicrobial properties, bionanocomposites developed by combining chitosan with other nanomaterials have proven to have enhanced activity. E.g., silver-loaded ZnO nanoparticles, when added to chitosan/gelatin, exhibited higher antimicrobial activity on E. coli and S. aureus [10], [20] presented the idea of incorporating positively charged chitosan nanofibers in the personal protective clothes/fabrics of the health care providers to hence enhance their protection, and safety. Companies such as Muse wearables (Consumex Industries, India), Organoclick (Sweden), Ryan Nanomedicines (China) are already implementing biobased formulations into PPEs and other materials. Researchers at Jawaharlal Nehru Center for Advanced Scientific Research (JNCASR), and CIIRC-Jothy Institute of Technology (India) have developed charge switchable polymeric coatings and polymer-based antimicrobial surface coating, respectively to protect against SARS-Cov2 virus [21]. demonstrated that polyphenol Catechin could be used to modify commercial cellulose fibres to produce antiviral masks. In another experiment [22]; we’re able to enhance the antimicrobial efficacy and applicability of Bombyx mori silk (which is used as a biomaterial in surgical sutures) by loading AgNP in the silk fibres produced from aqueous extract of Rhi- zophora apiculata leaf. These AgNP loaded silk fibres were able to inhibit >90% P. aeruginosa and S. aureus. Biobased polyurethane derived from renewable materials like algae oil and ricinoleic acid silver doped chicken egg-shell nanoparticles (AgNP) was found to be an excellent antimicrobial surfactant against gram-negative and gram-positive bacteria such as E. coli and S. aureus [8]. Preliminary evaluations by Ref. [23] on a modified coating using quaternary ammonium coating are highly effective against human coronavirus (HCoV) 229E, with remedia tion rate of >90% in 10 min and by > 99.9% after 2 h contact. These natural antimicrobial materials can be effectively utilized as linings and treatment materials to produce a range of biosafety equipment such as air filters, PPE and surface coatings (Fig. 4). Air filters depend on dense fibrous materials to stop particulate matter but the addition of antimicrobial materials such as polyurethane coated with methanolic extract of Euscaphis japonica or AgNP or Sericin from Bombyx mori or Grapefruit seed extract (GSE) or ethanolic extract of Sophora flavescens has been proven to achieve filtration efficiency in the range of 95–99.99% for common pathogens [24].

3. Post-COVID 19 biomedical market trends

COVID-19 has resulted in a rising impact of getting micro-encapsulated materials especially into several industries like food and beverage, pharmaceutical, and agrochemical businesses. Technological advancement, as well as the demand in the global market due to COVID-
19 impact, is anticipated to be a major aspect for the market growth. It is reported that several countries like US., U.K., Germany, France, China, India, Australia, South Korea, South Africa, etc., are expected growth of profits at global, regional, and country levels during 2019–2025 period (Fig. 5).

Microencapsulation method, which is mainly utilized for disguising taste, odor, and activities of the encapsulated structures, which in turn play the role as a useful ingredient to numerous applications of the pharmaceutical and healthcare sector. Sodium alginate, PVA, ethylcellulose, gelatin, and polysaccharides are among the ingredients used for microencapsulation technology [25,26,27]. The global trend has further witnessed a growing demand for the use of spray technology,
methods to manufacture beauty enhancements, manufacture of cosmo-textiles, increasing consumption of n-3 fatty acids for health, changing pattern of consumer spending have contributed the expansion of microencapsulation market, predicting better market growth (Fig. 6).

The projected period from 2019 to 2025 is providing a predictable growth of Polymer as a coating material of CAGR of 14.2%. A growth of CAGR of 13.3% is expected for pan coating, fluidized bed coating, and air suspension coating. Though uncertainty regarding the availability of the raw materials, is highly anticipated, this sector is promising a stable growth. To tap the customer base, strategic partnership between the firms are highly envisaged, though it invites growing competition between the industry members.

4. Conclusion and outlook

A variety of biobased materials, such as polyurethane, naturally derived nanoparticles natural antimicrobial agents, are emerging as the source of biosafety materials, while reducing the impact on the environment due to their usage and disposal. Some examples of green sources of antiviral agents that could become prominent include chitosan enhanced with green seed extract and green tea extract, poly-embedded polymeric hydroxybutyrate in combination with Cinnamaldehyde, copper nanomaterials, carboxymethyl chitosan polymers, essential oils incorporated into capsules, coatings, or films and ethylcellulose with acetoxy-polydimethylsiloxane bonded with clove essential oil. In the post-COVID-19 era, it will be important to prioritize biosafety using these greener materials. Although recent years have witnessed significant progress in the development of biobased antimicrobial materials, efforts are still needed to make them mainstream and economically feasible to produce at a large scale. The development of biobased materials to deter the growth and spread of pathogens that spread at a high rate such as COVID-19 is needed. Globalization has made these biothreats and pandemics a problem for every country, and global collaboration and cooperation is needed to tackle future threats. Hence research efforts need to be brought together and dissemination of information across the scientific community is needed to accelerate the development of biobased biosafety materials to secure the health and well-being of society and economic prosperity.

CRediT authorship contribution statement

Zeba Usmani: Conceptualization, Writing – original draft. Tiit Lukk: Writing – review & editing. Dileep Kumar Mohanachandran: Writing – review & editing. Vijay Kumar Thakur: Writing – review & editing. Vijai Kumar Gupta: Supervision, Writing – review & editing. Dave Robert: Writing – review & editing. Jog Raj: Writing – review & editing. Fabrizio Scarpa: Writing – review & editing. Raju Kumar Gupta: Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig. 5. Global microencapsulation market share, by application, 2018 (%) (Source: grandviewresearch.com).

Fig. 6. U.S. microencapsulation market share, by category, 2014–2025. A market valuation of USD 7.88 billion is reported for global microencapsulation market size in 2018. Expected growth of CAGR of 13.7% is notified for a period up to 2025 (Source: grandviewresearch.com).
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