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Recent advances and applications of polymeric materials in healthcare sector and COVID-19 management

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ABSTRACT

The coronavirus disease pandemic is considered at its worst and all nations are collectively fighting to improve global public health. In this outlook, polymers and their related materials (including plastics) are the primary sources in the manufacturing of medical and personal protective equipment. Plastics can be mass-produced, economical, and sterilized, which makes them an inevitable material in the medical and healthcare sector. Along with plastics, antibacterial and antiviral coatings, polymeric nanomaterials and nanocomposites, and functional polymers have become excellent materials for COIVD-19. This review centres on the applications of polymer materials in managing the COVID-19 outbreak. Moreover, the utilization of plastics with its healthcare applications are reviewed. Apart from this, major challenges and future directions of these materials have also been discussed. This review will help aspiring researchers to develop the basic understanding of polymeric materials currently employed in medical sector.

1. Introduction

The current situation with COVID-19 disease is a completely unprecedented global crisis. The experts have predicted through various calculations that this pandemic will have a devastating economic and social impact on the governments, corporations, and lives of people. The pandemic highlighted the image of plastic and gave it a makeover in the consumer market. Unlike previously taught, there is now an outlook among people that plastic products are safer than other recycled and reusable alternatives. Nowadays, plastics are not only discussed for their adverse effects on the environment, but also for their potential applications in household cleaning, PPEs, face shields, hygiene, and food storage materials to prefer household food [1,2,3]. Fig. 1 shows various applications of polymers in medical and healthcare sector. Although these crises will also lead to health issues and financial destructions, consumers will also lessen their leisure hours, travel, eating out, and other outings, which will result in lesser plastic consumption. Along with this, industries like automotive and electronics will also suffer tremendous uncertainty.

PPEs required by health workers are usually prepared from plastics. These are now widely used by medical professionals and other individuals in COVID-19 outbreaks to prevent themselves from the risk of infection. Disposable plastic needles have now completely replaced the other alternative equipment. Till now, no material other than plastic has shown a medical-grade potential and economical to manufacture protective garments and other medical equipment [4,5].

Plastics are appraised in the medical industry for their features like versatility, sterility, cost-effectiveness, easy usage, safety to patients, and also meets the requirements as given in Section 2.

Abbreviations: PPE, personal protective equipment; FDA, Food and Drug Administration; NPs, nanoparticles; H1N1, Human influenza A; H9N2, Avian influenza; RNA, ribonucleic acid; DNA, deoxyribonucleic acid; DPA, Defence Production Act; WHO, World Health Organization; ICMR, Indian Council of Medical Research; CDC, United States Centers for Disease Control and Prevention; LDPE, low density polyethylene; PP, polypropylene; PVC, polyvinyl chloride; PET, Polyethylene terephthalate; PC, polycarbonate; PES, polyethersulfone; PMMA, polymethylmethacrylate; HDPE, high density polyethylene; ASSOCHAM, Associated Chamber of Commerce; BMW-2016, Bio-medical Waste Management Rules—2016; UNEP, United Nations Environment Programme.

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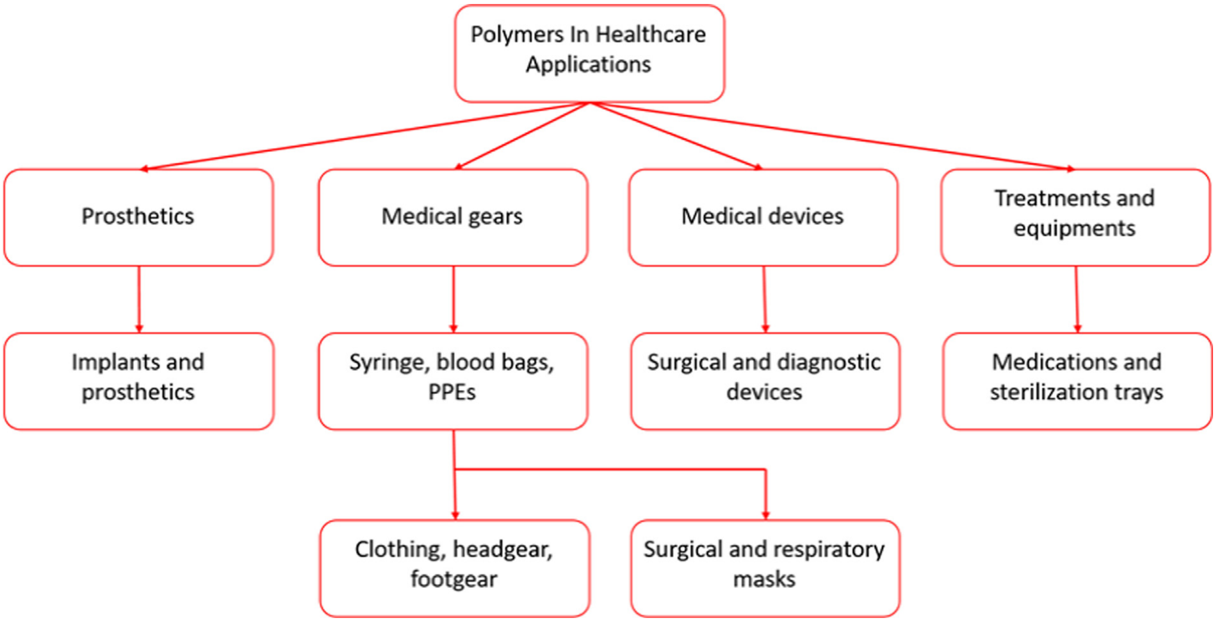

Fig. 1. Potential applications of polymers in medical and healthcare sector.

Table 1
Key factors to select materials for medical applications [6].

Sr. No.	Component	Specification
1	Mechanical properties	Stiffness, toughness, yield strength, compression/tension, and surrounding environment.
2	Surface properties	Friction, bonding, labelling, and printing.
3	Physical properties	Electrical conductivity, transparency, weight, shape/size, and dimensional stability.
4	Chemical properties	Resistance, degradation, and electro-magnetic capabilities.
5	Rheological properties	Viscosity, melt temperature, and shrinkage rate.
6	Biocompatibility and stability	Drug contact, skin/implantation compatibility, toxicity, irritation, and leachable.
7	Colour	Visually appealing, and moulding tolerance.
8	Feel	Substantial and device clicks
9	Cost	Competitive market and affordable.

It is predicted that plastics will always continue to provide efficient alternatives in future.

2. Selectivity of materials

While developing a medical equipment, selection of suitable material for every part is critical. This may range from the issue of physical performance and production constraints, to economic constraint and supply chain logistics. Few trivial components in identifying suitable material in medical sector are given in Table 1.

3. Applications

3.1. Antimicrobial polymers and coatings

Files The FDA stated that the spread of COVID-19 will highly affect the supply chain of medical products, including discontinuous supply and shortage of important medical products in the United States [7]. Additive manufacturing via 3D printing is one of its kind, well established to back up the insufficiency of medical devices. Research into additive manufacturing routes and developing antimicrobial polymers have made it possible to print and customize different medical devices. The only limitation for these polymers in the additive manufacturing of medical devices is their contamination with bacterial and other viruses [8,9].

Previously, copper has been widely used as a biocidal agent in bio-printing and other medical applications [10,11,12]. Apart from this, Cu nanocomposites are also utilized to improve the antimicrobial polymer properties for the evolution of medical devices [11,12,13]. It is proposed that the addition of Cu NPs to the polymer allows the development of medical devices that are resistant to bacteria growth. A strong biocidal effect of Cu was noted by examining the viral deactivation characteristics of copper oxide particles by infusing them with textiles. Borkow et al. [14] discovered that coupling copper oxide with protective face masks results in strong anti-influenza properties for protection from H1N1 and H9N2 influenza. However, when the commercial antimicrobial materials are implemented through printing specifications, it results in extruded layers and blocks the molecule of the size up to 0.000282 µm. This is gradually very small than the viruses like COVID-19 (0.03 ± 0.01 µm) [15]. The antimicrobial behaviour of Cu is usually enhanced either by (i) reducing the particle size of Cu to the nanoscale ($\sim$10 nm), raising the total volume of particles which can provide maximum surface area to liberate high amounts of metal ions in a solution or matrix, or by (ii) incorporating Cu NPs within the polymeric matrix. As compared to micro-particles and metallic surfaces, polymers infused with Cu NPs show strong antimicrobial activity by enabling the adsorption of microorganisms on the polymeric surfaces, thus activating the diffusion of water molecules via a polymer matrix. As a result, water with dissolved O_2 outreach the embedded Cu NPs surface, which releases the Cu ions and results in the corrosion process. After this, Cu ions damage the cell membrane of microorganisms permitting the flow of metal ions into the cell membrane and damaging the RNA, DNA, and any other bio-molecules. Cu ions as well as hydroxyl radicals lead to denaturation of DNA, thereby damaging the helix structure. This damage to nucleic acids deactivates the virus [16].

Therefore, the need for biocidal polymers during the pandemic, and the accessibility of additive manufacturing devices and materials could spur this research and revolutionize the development of medical devices. Therefore, the ease of use of antimicrobial polymer additive manufacturing technology is crucial for mask development to minimize the viral load on the mask and protect the user from possible contamination, when worn for a long time [17].

3.2. Polymer nanocomposites and nanomaterials

In order to prevent infections and loss of resources, the development of highly functional antiviral drugs is a need of time. Various functional NPs like quantum dots, nanoclusters, Si materials, carbon dots, Au and Ag NPs, graphene oxide, and dendrimers have shown excellent antiviral ability [18,19,20]. However, the antiviral mechanism and the efficiency of inhibitors is different in all cases, but their unique characteristics have made them better antiviral material. Lembo et al. [21] highlighted the antiviral effectiveness and mechanisms of these NPs. It is evident from previous studies that nanotechnology has greatly enhanced virus research [22,23]. Firstly, nanotech-based probes have shown great efficiency in virus detection, developing various bio-sensors and bio-electronics [24]. Secondly, nanomaterials prepared via virions and viruses-like templates have enhanced the biocompatibility and biosynthesis routes [25,26,27]. Thirdly, fluorescent nano-probes have been developed for their applicability in the molecular mechanism of virus-infected cells [28,29]. Finally, various functionalized NPs are reported to be highly powerful inhibitors of viral proliferation. Table 2 reports a few of the antiviral mechanisms for selected nanoparticles.

3.3. Plastics for personal protective equipment

Wuhan, the capital of Hubei, China was the hotspot of the SARS-CoV-2 (later named coronavirus and COVID-19) outbreak in December 2019 [36]. This virus kept on increasing and led to millions of cases all over the world. Due to its spreading and fatality, the coronavirus outbreak was declared a world pandemic. The executive government division of the U.S. also invoked the DPA to prioritize the domestic manufacturing of important medical supplies to fight the pandemic [37]. The health organizations like WHO, ICMR, and CDC have conveyed strict protocols for healthcare workers to ensure organizational safety. The mandatory use of PPEs (head to toe) was required. A range of plastics like LDPE, PP, PVC, PET, and PC is used in the manufacturing of these PPEs. After the initial few weeks of the COVID outbreak, the plasma transfusion from recovered individuals came up as an effective diagnosis option for affected ones. The blood plasma is collected by the process called plasmapheresis and the membrane used in it is usually made from PES, PMMA, or PP [38]. TyvekTM, manufactured by DuPont, is a bodysuit made from flash spun HDPE for workers exposed to high contaminated environments.

ASSOCHAM and Velocity reported that by 2022, India will produce 775.5 tons of medical waste/day with around 7% compounded annual growth rate [39,40]. In accordance with BMW—2016 under the Ministry of Environment, Forest and Climate Change, currently, 550.9 tons of medical waste are generated every day. All these predictions were made before the COVID-19 pandemic hit the country. Also, due to the COVID-19 pandemic, the amount of plastic waste generated continues to rise [41]. The UNEP estimated about 0.5 kg of plastic bio-waste that is produced by a single hospital bed/ day in the COVID-19 crisis [42].

3.4. Anti-viral coatings

NPs of metals and metal oxides (zinc oxide [43], cuprous oxide [44], silver [45], nano copper (I) iodide, gold NPs and silica) and a few Quaternary ammonium cations have been shown to inactivate different viruses. There are mainly two ways in which doped nano-active materials function against the COVID-19 virus: (i) it is evident that Ag NPs exhibit a replication of virus nucleotides, it attaches with the electron donor groups like S, O, and N, usually present in enzymes inside a microbe. Hence, the enzymes get denatured and disable the energy root of the cell, leading to a quick death of microbe; (ii) the Ag^+ cation may inactivate the COIVD-19 virus when it interacts with its spike protein S on its charge. It works in a much similar way as it does with HIV, Hepatitis, etc. [46]. Table 3 reports a few of the antiviral coatings and their mechanisms.

3.5. Nanotechnology-based coatings for mask fabrics

Professor Curran at the University of Houston is known for commercializing different nanotechnologies. He with his team is utilizing a hydrophobic coating he synthesized a decade ago for improving the effectiveness of surgical masks in order to minimize virus transmission. Curran initially launched his business of nanotech in 2013. Currently, he owns a company called Integricote, based at UH Technology Bridge, aimed to manufacture sealers for masonry, wood, and concrete. In spite of that, he has worked in nanotechnology fabric coatings since 2011, the technology that he is today employing to improve the protection from the viruses like SARS and COVID-19.

The method to fabricate a waterproof coating includes a substrate. Next, a surface having nano-scopic and microscopic characteristics is developed either by sol–gel consisting of saline or silane derivative and metal oxide precursor, or by other chemical agents. This technique may use the entire solution process or may require a controlled environment to develop a self-cleaning, waterproof coating to prevent the fabric from getting wet and stained [55].

Table 2
Antiviral mechanisms of nanoparticles.

Sr. No.	Nanomaterial	Virus	Mechanism	Reference
1	Graphene oxide	Respiratory syncytial virus	Directly inactivate virus and hinders attachment	[30]
2	Silver nanoparticles	Herpesvirus	Affect viral attachment	[31]
3	Gold nanoparticles	Herpesvirus	Prevent viral attachment and penetration	[32]
4	Ag_2S nanoclusters	Coronavirus	Block viral RNA synthesis and budding	[33]
5	Copper oxide	Herpes simplex	Oxidation of viral proteins	[34]
6	Zirconia nanoparticles	H5N1 influenza virus	Promote the expression of cytokines	[35]

Table 3
Anti-viral coatings with their mechanisms and action time.

Sr. No.	Category of Coating	Coating Material	Mechanism	Average time to neutralize viruses	Reference
1	Nanomaterials	Nano-CuI	Hydroxyl radical formation	< 4 h	[47]
2	Other	Powder from calcinating dolomite followed by hydration	Filtration	Not applicable	[48]
3	Nanomaterials	Ag NPs	Blocking interaction	< 4 h	[49]
4	Other	Viricide with essential oil	Not applicable	2–3 days	[50]
5	Nanomaterials	GO-Ag nanocomposite	Washing	< 4 h	[51]
6	Other	Chitosan incorporated *Azadirachta indica*	Not applicable	Not applicable	[52]
7	Other	Quaternary NH3 salt and polyhydric carboxylic acid (C_6)/ hydrocarbon group	Preventing elution of salts	2–3 days	[53]
8	Other	Tea extract, herbals, phytochemicals	Filtration	Not applicable	[54]

3.6. Functional polymers

The Prep FilerTM is a kit, newly launched by Applied Biosystems for the extraction of DNA from different forensic samples. The kid was examined against other commercially available kits for a variety of real forensic samples (like semen stains, hairs, nails, bones and tissues, bloodstains, skin swabs, saliva, and chemically treated prints). The Prep FilerTM kit is intended to isolate genomic DNA from other forensic samples. It uses magnetic particles embedded in a polymer much smaller than normal to provide large surface area and efficient DNA binding, allowing for maximum DNA recovery [56].

4. Conclusion

Polymers (including plastics) have revolutionized the healthcare industry, mainly single-use plastic. This paper suggests how polymers are helping in dealing with the world pandemic. The COVID-19 outbreak immensely increased the use and dependence on plastic products in an unpredictable manner. Medical plastic is considered infectious and thus, cannot be discarded as common municipal waste. Most of the healthcare plastic is now a potential feedstock to the petrochemical industry to produce fresh plastic or refined fuels. The outcome may be devastating and will affect our future generations. Although plastic is effectively helping in containing the virus and infections, still urgent measures are required for its segregation, sterilization, and recycling.

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.

Acknowledgements

All authors have contributed equally.

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