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Significance of additive manufacturing amidst the pandemic

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ABSTRACT

In the light of COVID-19 pandemic, a global shortage for Personnel Protective Equipment (PPE) led to the search for an alternative to fill the gap where additive manufacturing made necessary development of rapid design and adaptive filtering masks for local manufacturing using 3D printing to help the frontline workers. The review focuses on the utilization of antimicrobial materials in additive manufacturing with the use of bespoke design to facilitate and respond to the disruptions in the medical supply chain. Previous studies confirmed the age-old theory of copper as an antimicrobial material with contact killing properties. The antimicrobial properties of copper have been registered at the U.S. Environmental Protection Agency as the first solid antimicrobial material. Combining the properties of copper in a PLA (Polylactic Acid) filament as a nano composite, Copper-3D facilitates the antimicrobial properties to any 3D printed object. Provided this flexibility of 3D printing, the use of masks designed distinctively based on the 3D scan of an individual's facial structures as an efficient Personnel Protective Equipment is also addressed. Additive manufacturing as a support to the shortage of medical devices and a responsive method to the disruption in the supply chain is discussed.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Processing and Characterization of Materials.

1. Introduction

The recent pandemic has economically affected many nations and still has its effect on many. The World Health Organization has come up with numerous protocols in various directions to cut off the spread. Thus, due to this effect there have been a huge demand created for the medical supplies to fight against the pandemic. The government has foreseen the break down and disruption of the supply chain due to the restriction and lockdown in effect. The supply of such critical products must go through various inspections to be transported from one district to another. This is due to the lock down in motion at different districts to stop the spreading. Especially the products which are in demand are the medical products such as gloves, masks, sanitizers, face shields, and more. During this pandemic the frontline of the battle is taken up by the doctors, nurses and *para*-medical staff making them vulnerable to the virus given that 412 Medical staffs including doctors are affected as of April 22, 2021 and around 150 medical staffs have lost their lives in India. COVID-19 is highly infectious and due to the lack of resources the medical personnel must conserve themselves during these critical periods. The medical personnel have been under great stress to conserve, serve for longer duration and to be precautious during their routine [1]. The lack of resources has created physiological effect on the medical personnel during their exposure while treating the corona affected patients. This is mainly due to the disruption in the supply chain of the medical products during the lockdown period and the increase in demand has taken its toll. Thus, resorting to additive manufacturing will be effective as it is well suited to support in developing the medical products which is in demand and this could also eliminate the possibility of spread as the supply chain is required initially to set up only. With advancements in technology and additive manufacturing, it is becoming less complex and more common to print the required medical devices with ease and importantly at the need of time without delay [2]. The studies of antimicrobial properties of copper are relatively a recent development in the last decade which has gained value and nearly 300 different copper surfaces have been registered as antimicrobial properties with the Environmental Protection Agency [1]. The contact killing is the action involving the termination of virus/pathogen function when it comes in contact or exposed to surface of the copper or alloys of

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copper. The metal surface releases charged particles called ions which is significant enough to cause cell damage. Most studies have been related to contact killing, a wet inoculation technique which was done by applying 20 µl of cell suspensions to coupons. This was a valid approach for laboratory testing only and might not mimic well with the dry method, but the approach was done with volumetric of liquid swabbed with cotton and placed over the coupons, the liquid placed evaporates instantly and allows direct contact of the experimental subject with the metal surface. Under this type of condition, the *E. coli* and other bacteria have been inactivated after few minutes of exposure. This states that dry metallic copper surfaces are having antimicrobial properties than the moist ones. In recent publication by the 'The New England Journal of Medicine' by Van Doremalen et al, suggested that the copper material was more effective in decreasing the COVID-19 virus viability, predicted decay and Half-Life reduction. The author based upon the Bayesian regression model stated that the polymer, polypropylene, and stainless steel have showed a low median Half-Life reduction. But when exposed to the copper surface, the Half-life was reduced after nearly exposed to an hour that is 0.774 h [1]. Thus, stating that the copper material used in day-to-day life could reduce the exposure to bacteria and viruses. In ancient civilization the material used to store eatables and water were made up of copper and its alloys, this indicates that they have understood the antimicrobial properties of the copper. For better understanding that copper being antimicrobial material, copper releases copper ions [Cu^{2+}] when virus is exposed to copper surface, these copper ions cause cellular damage to the virus. The cell membrane is eventually damaged and other stress phenomenon lead to collapse of the cytoplasmic content inside the cell. These studies clearly state the antimicrobial property of copper and its alloy [3]. There are two approaches to produce antimicrobial copper material, one is reducing the size of the copper particle to a Nanoscale and other in a matrix form to increase the incorporation over the total surface area. This allows the additive manufacturing to be best suited to incorporate the Nano copper matrix with other materials. In this paper we have designed antimicrobial mask which will be incorporated to medical staff who have been the frontline to fight against the COVID-19. This mask is incorporated with the antimicrobial material and specifically designed to fit each individual; this is done with the help of an imaging process. A new approach to design of antimicrobial material to be incorporated with the air filtering system has also been discussed, as this system circulates the air in a building which when fitted with the antimicrobial nanomaterial could create a defense to fight against the viruses [4]. Followed with the identification of public places where the exposure is more and how these places could be incorporated with antimicrobial copper nano material to protect and fight against the viruses. Especially in countries like India the public areas are much exposed and thus to create defensive ways to fight against the pandemic is very important to stop the community spread. Thus, with the help of additive manufacturing technique this is possible as it incorporates the nano copper material with other products which could be used as a defensive technique [5]. This is also the best method as the other method of production could consume large quantity of raw material and we would have to device a method to reuse the wastages. But with the help of additive manufacturing the demand of the nanomaterial could be monitored and this allows us to meet the demand effectively.

2. anti-microbial mask

Coronavirus is an efficient virus in transferring itself to other beings, in the war against it, doctors in frontline are the most susceptible to catch the virus which is a higher risk factor. Use of masks and gloves would be the first-hand defense against the virus, these protective gears must be in a constant development as viruses such as these evolve. The further development of a face mask can be done by the method of production and additional attachment modules to improve the filtering of various types of airborne viruses and chemical fumes [6]. The development of an antimicrobial polymer as the filtering layer in the mask would be a critical advantage, for which copper could become the key element. Copper has been used for utensils in the past as it has the ability to disinfect. The Environment Protective Agency has recognized alloys of copper and nano copper material having antimicrobial properties [7].

Nano particles in a polymer matrix increase the antimicrobial properties than a direct metal surface exposure as it would allow the absorption and exposure to nano particles at a much faster rate. Copper with its disinfectant characteristics, can be implemented in a mask to give it an antimicrobial property. Copper can be one of the filtering layers or be the raw material to print the mask [8]. The filament for 3d printing is infused with nano copper out of which the mask can be made from, giving it antimicrobial properties. Zuniga. J [9] showcased that a commercially available antimicrobial additive manufacturing polymer of Copper3D was effective as much as 99.99 % against Escherichia coli and Staphylococcus aureus. PLACTIVE AN1, an innovative product developed with PLA suits uniquely for additive manufacturing which is an integrated nano copper additive available in 3D filament. Implementing these during the pandemic with a disrupted supply chain is a challenge and allows showcasing the benefits of antimicrobial material used for developing medical PPE and the development of additive manufacturing. N95 face mask respirators commonly used as PPE during the pandemic situation recognized by National Institute for Occupational Safety and Health uses a filter material capable with 95 % filtering efficiency, the masks filter out contaminants like dusts, mists, and fumes. The minimum size of 0.3 µm of particulates and large droplets will not pass through the barrier, according to the Centres for Disease Control and Prevention [10]. The filter is a tough yet flexible material which is an electrostatic non-woven polypropylene fibre. In addition to this filter there can be an additional antimicrobial filter layer which is infused with copper nano particles. Dankovich [11] incorporated copper nanoparticles into paper for the purpose of water purification. He used an environmentally benign method for the direct preparation of copper nanoparticles, by in situ preparation in paper. The copper ions were reduced with ascorbic acid [12]. Copper nanoparticles (Cu-NPs) were formed in less than 10 min and were distributed on the paper fibre surfaces. The Cu-NP papers with higher copper content showed a high bacteria reduction of log 8.8 for E. coli. The paper sheets containing copper nanoparticles were effective in inactivating the test bacteria as they passed through the paper [11]. Manufacturing of this Cu-NP filter can be made inhouse within the hospital, giving it the flexibility in stock management and eliminating the risk of contamination from outsourcing. An experiment was conducted by N. V. Tien [13] who was able to embed a polyester filter cloth with copper nanoparticles by a green chemical method, they were generated in situ on pieces of commercial polyethylene terephthalate (PET) filter cloth by reducing $[Cu(OH)_4]^{2-}$ ions with ascorbic acid in an aqueous solution. The analysis from a scanning electron microscope (SEM) image showed that the sizes of synthesized copper particles were less than 100 nm to over 500 nm. An increased copper nanoparticles load on the filter resulted in increasing antibacterial effect. Using this method copper nanoparticle can be infused in a breathable material which is to be used as one of the filters upon which there should be another conventional filter. A direct study [14] which made copper nanoparticles infused on a cotton fabric by an in-situ synthesis was carried out by using a chemical reduction method. Copper sulphate as a precursor, protective agent against oxidation of nanoparticles and citric acid as a stabilizer along with sodium hypophosphite as a reducing agent were used. This study proves the possibility of using a breathable copper infused material as a filter.

The mask is designed to incorporate a conventional N95 and copper filter which is fitted by resting on a frame to prevent it from flexing due to breathing and retain its shape throughout. The mask can also be fitted with a soft material layer over the facial contact surface of the mask for comfort and reduce fatigue due to long use. The mask has a breathing valve opening of 40 mm diameter, where the filters are of compatible sizes to fit within and is held together by a filter lock which is removable and attachable by a press fit. The design of the mask can be further improved with an exhale valve for ease of breath and various other functional improvements can be done from a product standpoint.

To sum up, the Copper and its alloys are known best by their antimicrobial properties. The Cu ions in their excited state are able to terminate the microbe by destroying the cell membrane. COPPER3D produced polymer is proved to be 99.9 % efficient against microbes and can be used to produce the antimicrobial filter. The N95 masks has a higher filtering efficiency but is inefficient in filtering particles less than 0.3 µm. The design of the new mask involves an ample modification in the traditional and more common N95 mask can be done by adding copper infused nanoparticle filter, a filter frame and a filter lock as shown in Fig. 1.

3. Bespoke antimicrobial mask

Face mask is a key protective gear against any airborne viruses as they are intended to filter and help the individual to breathe without catching the virus. Masks do perform an excellent job preventing viruses from getting through [15]. There is always a new virus emerging or evolving which might require a totally different protection equipment, in such case there shall always be a protective antimicrobial element which could influence the viruses. Surgical masks do not perform as an efficient facial protective equipment due to the loose fit between the face and mask allowing small particle and large droplets. An experiment on testing the efficiency of facial masks by Abhiteja Konda [16] suggested that even a 1 % gap between face and mask dropped the efficiency of the mask down by half or more. The loose fit of a face mask is a major drawback which can be substituted with a fixed shape mask designed to fit on the face reducing the gaps, designed to have an opening for the filter with a modular design to interchange filters [17]. Thus, this mask can be used after sterilizing and replacing the filter with a new one, thus reusing it for a couple of time is possible. Every human being has different facial structure, where the fixed shape masks cannot snuggly fit on the face leaving gaps as it is only designed for a generic face structure. Using the help of additive manufacturing techniques and modern methods of 3d scanning, the masks can be made to function even more effectively. Faces of each individual who intend to use the mask is scanned in 3 dimensions to upload the facial structure in a 3d software to design the mask for the individual, upon which the designed CAD file is converted to STL format which is then printed using a 3D printer. A typical firm such as Materialise Mimics can do the function of scanning and printing 3D objects based on person specific approach to manufacture bespoke masks. LIDAR and augmented reality can also be used to measure the shape and size of the face of an individual, a feature which is more common in today's smartphones. This provides the perfect fit over the face without leaving obtrusive gaps for the particles to enter while breathing. The design allows the mask to be reused and with modular design for interchangeable filters. The face of the individual is scanned and uploaded in the 3d modelling software based on which the mask body is designed to fit perfectly without leaving any gaps, providing a perfect fit on the face and is designed with function and comfort as the design priorities [18] (Fig. 2).

Manufacturing these unique face masks for every person in demand with injection moulding is very inefficient and requires lot of resource and development for designing the moulds for every mask, and would not pay back as it is a low volume production method and thus either the product would be extremely costly or the production facility would have to run at a huge loss. The masks are unique to each other and required in less quantity, for which additive manufacturing would be the right manufacturing method to produce these masks. The material used for the mask shall be of Poly Lactic Acid (PLA). Polylactic acid is the main commodity polymer derived from corn which is a renewable form of source. The manufacture of antimicrobial equipment's from a renewable resource could significantly keep in touch with the demand during the pandemic situation. The filament for 3d printing is infused with nano copper out of which the mask can be made from, giving it antimicrobial properties. Zuniga J. [9] showcased that a commercially available antimicrobial additive manufacturing polymer of Copper3D was effective as much as 99.99 % against Escherichia coli and Staphylococcus aureus. PLACTIVE AN1 an innovative product developed with PLA which suits uniquely for additive manufacturing and is integrated with nano copper additive available in 3D filament [19]. The used mask can be sterilized and the plastic material can be removed to return it to the manu-

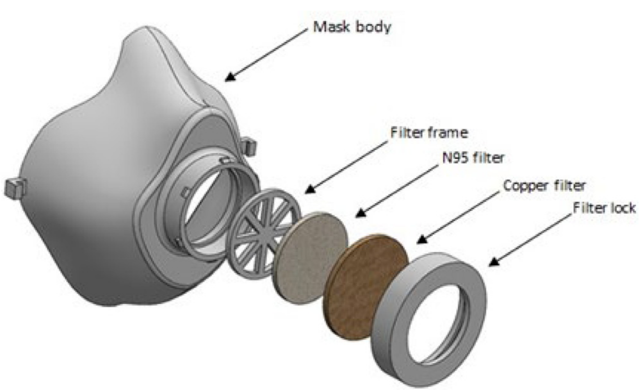

Fig. 1. Antimicrobial masks with its filters and components.

Fig. 2. Mask designed for a 3D scanned face for perfect fit and comfort.

facturer for a recycle process which would reduce the plastic waste and the same can be used again as filament for the further mask manufacture. Indian Medical Association (IMA) reports that 1,300 healthcare workers across the country have been tested positive and 99 doctors have died due to COVID-19, as of July 16, 2021. Given this, every frontline worker should be provided with a custom fit mask to protect them against the airborne viruses, which have a complete gap free fit of the mask over the face. The bespoke masks can be further expanded to the public where they can 3D scan their faces and have their masks designed by doing so, they can carry around the mask file and have them printed by any 3D printing company. This could be incorporated in secure buildings where high-level priority is necessary along with a dedicated additive manufacturing unit and with the safe disposal of the same as shown in Fig. 3.

To summarize, a Mask is designed based on the facial structure of the individual obtained from the 3D scan of the face and is designed to give a perfect fit and provide comfort. The mask body, filter frame and lock are 3D printed using a copper infused PLA filament available from Copper3D. The copper filter is prepared from a cloth by in-situ process and N95 filter is used, these are assembled with a memory foam to comfort the use of the mask over the individual's face. The mask and copper filter can be prepared in house. A 3D printer farm can be used to meet the demand. The improper disposal and reuse of masks and respirators might further increase the risk of secondary transmissions and the trans-

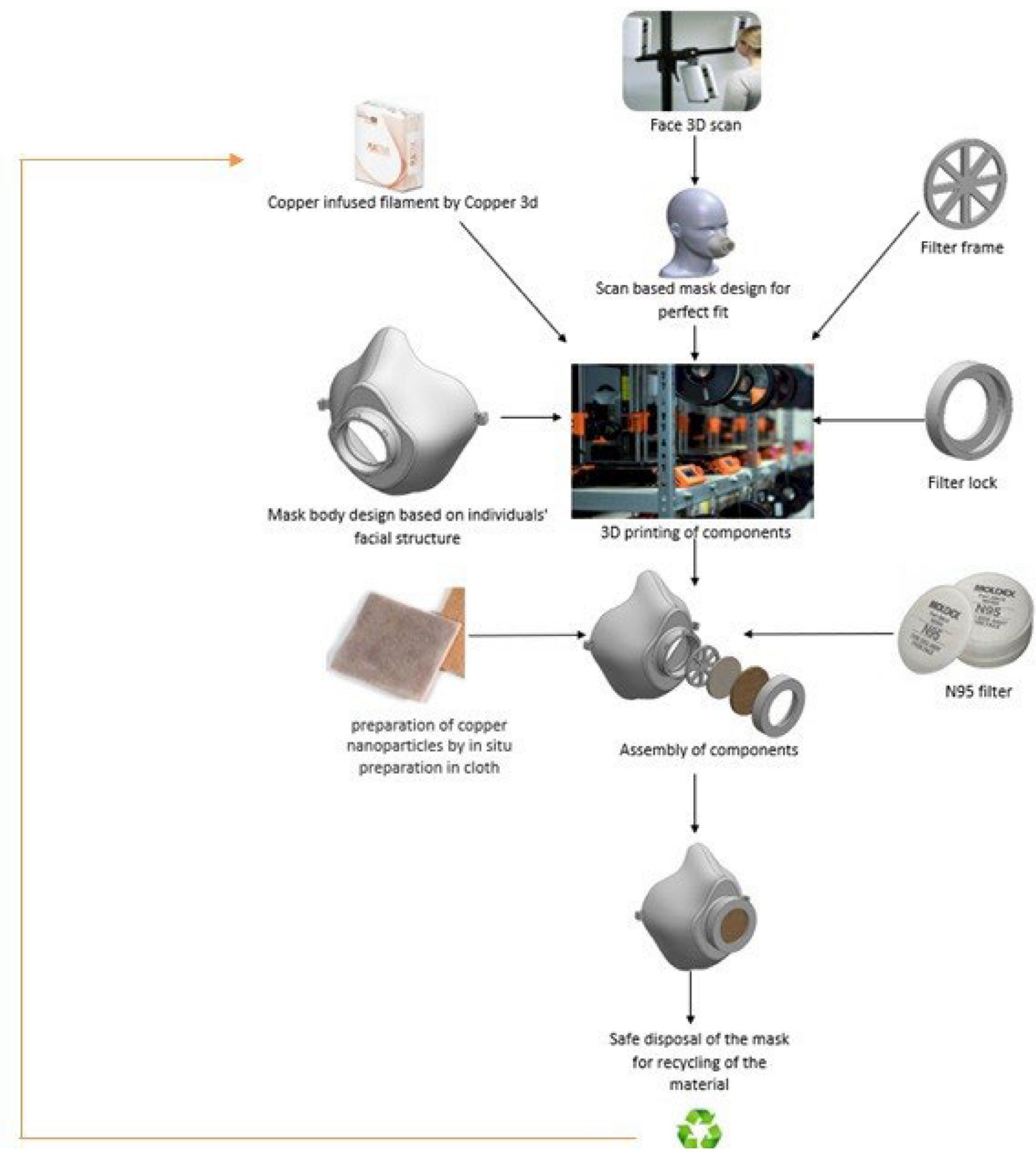

Fig. 3. Life cycle of a printed mask.

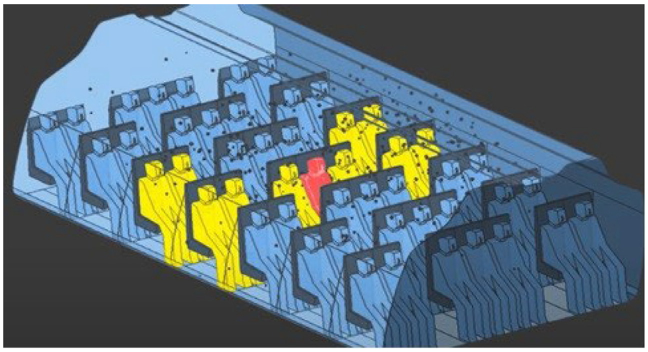

Fig. 4. Simulation by Yan Chen, Q of Purdue university.

mission of the COVID-19 from the recycle process by itself might be a tedious process. Although sterilization processes such as Hydrogen peroxide, ethylene oxide, bleach and UV treatments can be performed on these masks for a proper recycle of the materials. To simplify the process, it can be sent to the manufacturer, where it can be recycled with necessary recycle procedures and hence the 3D printed plastic waste can be reduced, and the same can be used again as filament for the further mask manufacture.

4. Antimicrobial air purifier

Viruses can spread through sneezing, coughing, and shaking hands with a sick person. The person is exposed to the virus first-hand when they touch any contaminated objects. Poor ventilation, dirty air conditioner or HVAC system will help speed up the spread of bacteria and viruses. An air-conditioned room tends to be closed and lacks exterior ventilation and when a sick person in the room sneezes, the atomized droplets tend to recirculate within the room. The distribution of the infectious agents contained in the expiratory droplets of an infected occupant in an indoor environment is transient and non-uniform. The risk of infection can thus vary with time and space. An air-conditioner works by recirculating the air at room temperature which when passed through the evaporator at lower temperature, heat transfer occurs to reduce the air temperature and is circulated. Air-conditioned room is most contagious if an infected person sneezes, the expiratory droplets of an infected person in an indoor closed environment tends to reach everywhere in the room. The spread of these droplets is no exception to hospitals, patients with a contagious disease is highly probable to spread the disease. An air purifier with antimicrobial filters would be of high importance to prevent the circulation of the contagious pathogens. Implementing a series of filters in the air conditioner with antimicrobial filter layer could serve the purpose as air purifier and an air conditioner. Airlines recently have decided to block the middle seat where people are not allowed to sit in the middle row to keep social distancing even while flight, this is a controversial decision and is proved to be ineffective by various study of flight cabin air flow simulations, Jitendra K. Gupta [20] from Purdue university made a simulation of airflow which predicts the flow of air from the HVAC system to the passengers nearby as shown in the simulation diagram. The expiratory droplet cloud from passenger in the middle moved in the cabin with the bulk flow. The local droplet concentrations in the zones where the droplet cloud reached first were high, as the cloud was dense for the initial period. It was observed that the droplets eventually dispersed to all seven rows, but the droplet concentrations in the row furthest from the index passenger were relatively low, this shows that irrespective of the middle row vacancy, there will always be continuity in air flow inside a confined environment.

Fig. 4 shows a Boeing 747 cabin where the corona positive passenger in the centre sneezes and the highlighted people are vulnerable to infection as simulated by Yan Chen, Q of Purdue University. The local droplet concentrations in the zones where the droplet cloud reached first were high, as the cloud was dense for the initial period. It was observed that the droplets eventually dispersed to all seven rows, but the droplet concentrations in the row furthest from the index passenger was relatively low, this shows that irrespective of the middle row vacancy, there will always be a continuous recirculation of air flow in a confined environment [21].

An antimicrobial filter in an air-conditioner would benefit in any case where the circulation of air containing virus can be controlled using the antimicrobial filter. The filter can be made of copper nanoparticles. An increased copper nanoparticles load on the filter resulted in increased antibacterial effect. Using this method,

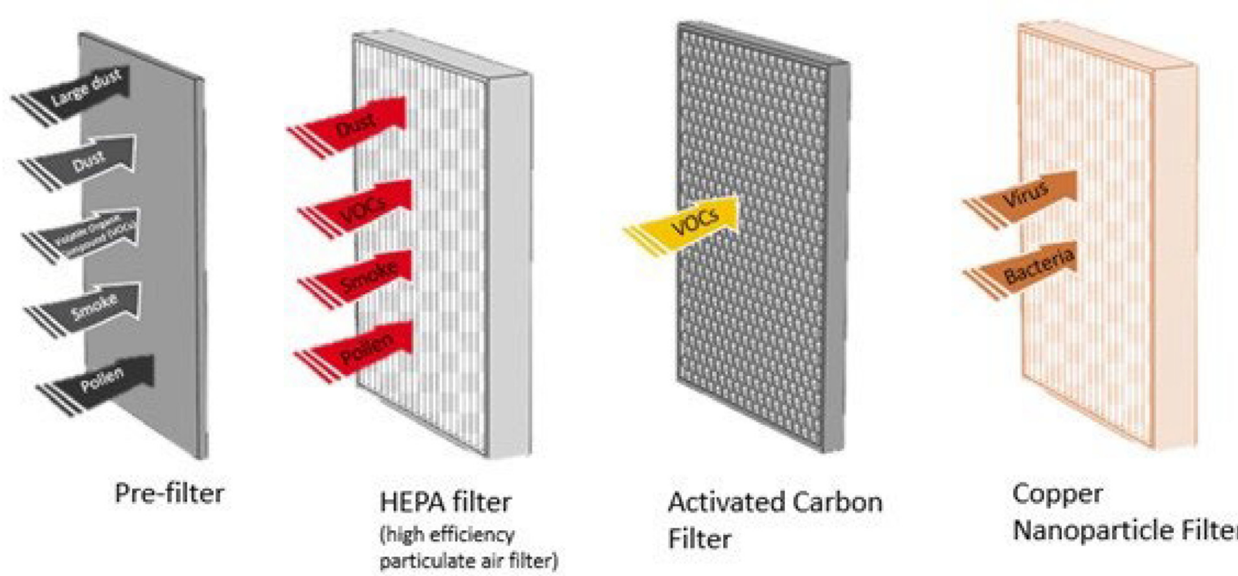

Fig. 5. Air purifier filter layers with nanoparticle filter.

copper nanoparticles can be infused in a breathable material which is to be used as one of the filters upon which there should be another conventional filter which could help control the recirculation of the virus in the air-conditioned environment as shown in Fig. 5. The filter can be incorporated in an air conditioner or as a separate air purifier unit. A direct study [14] which made copper nanoparticles infused on a cotton fabric by an in-situ synthesis which was carried out by using a chemical reduction method. Copper sulphate as a precursor, protective agent against oxidation of nanoparticles and citric acid as a stabilizer along with sodium hypophosphite as a reducing agent were used. This study proves the possibility of using a breathable copper infused material as a filter. A recent claim by 239 scientists state that coronavirus is an airborne disease, furthermore, emphasizes the need for an antimicrobial air filter in these hard times. The air from an infected person tends to stay airborne by recirculating in an air-conditioned space and potentially increase the spread due to air flow from the blower of an air-conditioner [22]. Due to the recirculation of an AC, the airborne virus tends to spread and reach out a larger area than in a stationary environment. An air-conditioned medical centre could become the hotspot for spreading the virus, anyone without a PPE would be vulnerable to be infected. An air purifier with HEPA filter can potentially filter Volatile Organic Compounds (VOCs) and pollution particles, but these do not act against infectious viral pathogens as they are less than 1 μm, which makes it impossible to filter these. Adding an antimicrobial copper nanomaterial filter, the viral pathogens are subjected to the contact killing ability of copper and the virus can be controlled over time. The filters can not only be in an air purifier, but also in an air-conditioner which could control the spread of the pathogens overtime.

5. Common point of contact in public areas and its antimicrobial replacements

Few common places of contact in the public during the pandemic have been identified and possibilities on how these could be addressed with the help of antimicrobial material and additive manufacturing process is shown in the Table 1. This helps us to utilize the 3D printing in an effective manner to fight against the pathogens in the current state and to be prepared in the future.

Above table shows identified common contact places with possible replacement/Attachment modules which can be manufactured using Additive manufacturing.

6. Result

The various approach with the help of 3D Printing or additive manufacturing is uniquely well suited to aid a hospital or a medical Centre when there is an unavailability of medical supplies in an instance such as the corona virus pandemic, when supply of medical PPE was in shortage which with an in-house 3D printing farm can facilitate the production of PPEs such as masks. The contact killing characteristic of copper gives it antimicrobial properties, using this in a PPE and manufacturing it within a hospital closes the supply chain and opens door for enhancement by making PPE antimicrobial. A face mask with a loose fit leads to reduced efficiency in the ability of the mask to protect against pathogens, a mask can be designed for an individual by 3D scanning, which would allow the mask to have a no gap fit on the face, aiding the mask to perform its desired function efficiently. The mask can be

Table 1
Additive manufacturing replacements for common touch areas.

Commonly used items	Replacement/Attachment modules	Description
Hanging IV Drip stand 	Two-piece cylindrical fixtures 	An IV drip stand is one of the most touched equipment by the patient and healthy nurses. The point of contact of the stand can be covered by a PLACTIVE 3D printed two-piece antimicrobial fixture made from PLACTIVE copper infused filament.
ATM keypad 	Alternative copper nanoparticle button replacement 	An ATM keypad is widely used by every-one and is subjected to large exposure of microbial residues. The buttons can be 3D printed accordingly using the copper infused PLACTIVE filament which would have antimicrobial properties. This could also be used for card swiping machines which is used at a higher rate
Hospital bed rails 	Two-piece cylindrical fixture 	Bed railings are equally the most common contact regions in a hospital, this can be similarly covered by a two-piece fixture which can be 3D printed from PLACTIVE, a copper infused filament with antimicrobial properties. Also, could be used for the super market carts where public exposure is more.

3D printed using copper nanoparticles infused filament available from manufacturers such as Copper3D. The used material can be sterilized and can be sent back to the manufacturer for further recycling, thus reducing waste and avoids pollution. This allows us to implicate the industrial symbiosis through small steps and in different sectors. The filters are to be made by deposition of copper nanoparticles using in-situ method providing it antimicrobial properties and this can be used in the mask alongside conventional N95 filters. The copper nano particle filter can be utilized in an air purifier or in an air-conditioner, thus reducing and controlling the viral pathogens over time. The common contact regions by public should be given the antimicrobial treatment by attaching or replacing the objects with 3d printed copper nanoparticle infused material which could assist in the war against pathogens. Many countries are trying to educate the society through various ways about the spread of the pathogens but in spite of that people are careless about the community spread. Thus, in order to enhance the safety of the society the above techniques would be adaptive and sustaining for most people.

7. Conclusion

In conclusion we can say that additive manufacturing is placed uniquely to support the shortage of medical devices. Also, this states that the research interest in developing antimicrobial material have been increased and with the help of rapid prototyping various medical equipment can be printed at the critical moment. Many open sources for critical medical devices state a common problem with respect to sterilization being difficult. Thus, the polymer gives an alternative for such problems with incorporating with copper nano particles and provides a potential pathway to inactivate the COVID-19 virus when it comes in contact with the surface of medical products which is manufactured with antimicrobial material. The use of additive manufacturing will be offered to different states to produce the medical products and to increase the safety aspects of the medical personal as well as the affected patients to have a fighting chance. The custom fit design of a mask for an individual increases the effectiveness of using it alongside the antimicrobial filters, such feature is endorsed with the help of additive manufacturing and could be a staple in the world of pandemic. Thus, other critical medical products can be produced to facilitate and respond to the disruptions of the medical supply chain [23]. In the next decade, antimicrobial material and additive manufacturing will play a major role in the manufacturing of on demand medical supplies. The disruptions in supply chain of certain materials could be prevented by printing them within the healthcare premises and this could enhance sustainable manufacturing as well as a sustainable supply chain. More focus on the study of copper infused PLA filaments has to be done. Furthermore, the carbon foot prints of the printed materials are to be studied to know and identify its impact on the environment to enhance the sustainability of the process.

CRediT authorship contribution statement

M. Nishal: Methodology, Project administration. **K. Ramprasad:** Conceptualization, Resources. **M. Salman Dasthageer:** Writing – review & editing, Visualization, Formal analysis, Investigation, Validation. **AG. Ragunath:** Writing – original draft, Software.

Data availability

Data will be made available on request.

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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