3D Printing Technology in Fighting the COVID-19 Pandemic

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The coronavirus disease 2019 (COVID-19) rapidly spread to over 180 countries and abruptly disrupted production rates and supply chains worldwide. Since then, 3D printing, also recognized as additive manufacturing (AM) and known to be a novel technique that uses layer-by-layer deposition of material to produce intricate 3D geometry, has been engaged in reducing the distress caused by the outbreak. During the early stages of this pandemic, shortages of personal protective equipment (PPE), including facemasks, shields, respirators, and other medical gear, were significantly answered by remotely 3D printing them. Amidst the growing testing requirements, 3D printing emerged as a potential and fast solution as a manufacturing process to meet production needs due to its flexibility, reliability, and rapid response capabilities.

COVID-19 | 3D printing | additive manufacturing | medical applications | open-source files

1. Additive Manufacturing (AM)/3D Printing in Medical Applications during COVID-19

1.1. AM/3D-Printed Personal Protective Equipment (PPE)

PPE acts as a shield between users (generally healthcare professionals) and pathogens. All healthcare professionals must use PPE to reduce the spread of pathogens during pandemic-like situations [1]. PPE is subjected to the FDA enforcement guidelines, but the Food and Drug Administration (FDA) relaxed its guidelines, citing an attempt to help greater availability of PPE during the public health emergency. The new FDA guidelines for the COVID-19 pandemic do not object to the distribution of improvised PPE as long as they do not cause any "undue risk" [2]. With the FDA's relaxed guidelines on PPE regulation, there has been a clear indication of the need for 3D-printed PPE [3]. Due to AM's versatility, Ford Motor Company could 3D print PPE at its Plymouth, Michigan, plant, producing roughly one million face shields per week [4]. Czech-based Tech giant Prusa Research began sharing open-sourced face shield designs, allowing anyone with a 3D printer to download and use the design file to print [3]. Many hobbyists have 3D-printed PPE to help local hospitals with the severe shortages [4]. For the first time, the 3D printer home-user community has joined hands to produce PPE in large numbers. It has been proven that more than 180,000 users worldwide could produce up to 6 face shields in 10 h, each on average, depending on the designs and capabilities of the printers. Greece, having about 500 printers, could produce more than 6000 face shields in a single day, and this was enough to equip its nurses, doctors, rescuers, and staff working in contact with patients [1].

1.2. AM/3D-Printed Nasopharyngeal Swabs

The SARS-CoV-2 virus that causes COVID-19 disease can be detected through respiratory samples by reverse transcription-polymerase chain reaction (RT-PCR) or other molecular methods [5]. Nasopharyngeal (NP) swabs are the devices used to capture respiratory mucus and epithelial cells and release the mucus matrix into a transport medium. The transport medium can be analyzed to find viral RNA [6]. The NP swabs must serve three essential functions: (i) must pass through the nasal cavity easily and comfortably; (ii) must collect enough mucus to test for viral RNA; and (iii) should be capable of releasing the collected sample in a manner that will not interfere with the RT-PCR test [7]. The surge in COVID-19 testing has caused an acute global shortage of nasal swabs [8], and access to NP swabs remained a bottleneck for COVID-19 testing in some regions of the world [9]. Using 3D-printed NP swabs to collect nasal samples for COVID-19 testing is feasible, acceptable, and convenient for local production [8]. The FDA classified 3D-printed NP swabs as a Class I, 510(k) Exempt in vitro diagnostic medical device [10]. Formlabs, a 3D printer manufacturer and technology developer, has used its printers to manufacture up to 100,000 nasal swabs daily to tackle these shortages. Printed swabs were shipped to hospitals across the United States that needed early coronavirus detection supplies [11]. Formlabs has used surgical guide resin indigenously developed and specially designed for their printer [12]. Decker et al. [5] printed NP swaps using autoclavable surgical-grade resin (Surgical Guide, Formlabs) and compared them with the conventional Flocked Nasopharyngeal Swabs (FLNP). The 3D-printed swabs displayed statistically identical results to standard FLNP in a head-to-head clinical trial, making them a viable option in COVID-19 testing requirements. These researchers have concluded that 3D printing technology can provide an alternate strategy for swab shortages by facilitating a local solution to FLNP shortages [5]. Sarah et al. [13] printed nearly 2000 swabs using PLA in FDM printers and sterilized them using low-temperature plasma, and these swabs cost them as little as USD 0.05. Nicole et al. [9] designed and printed the NP swab using stereolithography (SLA), as exhibited in **Figure 1**, and made their design open-access. These designed swabs also absorbed a significant amount of mucus and passed the abrasion and handling tests.

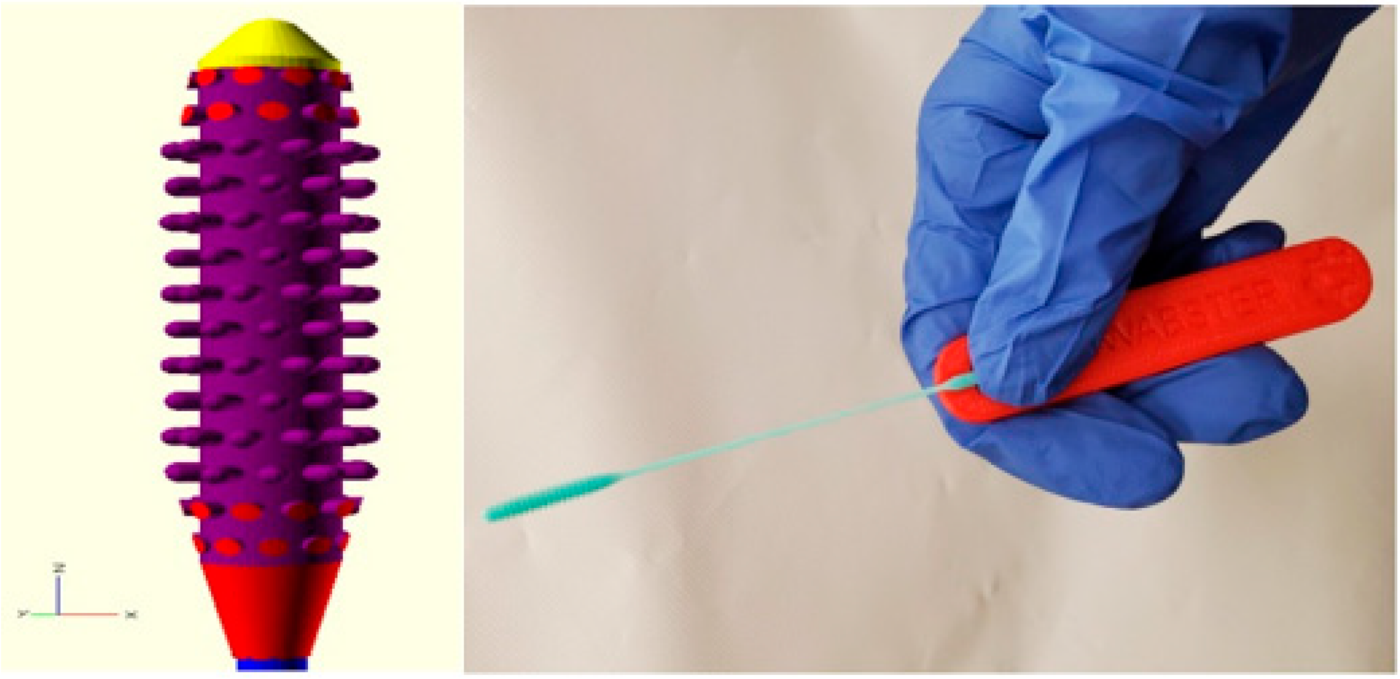

Figure 1. CAD representation and SLS-printed NP swab [9], open access.

Ian et al. [7] developed lattice bulb NP swabs using Digital Light Synthesis (DLS). These lattice swabs showed efficiency in early clinical trials and met all necessary criteria for an NP swab. Pediatric nasopharyngeal swabs (mini swabs for kids) are a smaller, thinner, and more flexible version of NP swabs used for adults. Pediatric nasopharyngeal swabs faced more severe supply scarcity during the coronavirus pandemic than adult swabs. Starosolski et al. [6], at Texas Children's Hospital, printed NP swabs using surgical resin. Their work aimed to provide pediatric NP swabs for kids of 1–3 years of age. After sterilization, printed mini swabs were subjected to tensile, torsion, flexural, and fluid absorption tests. Pediatric NP swabs have proven their usability and efficiency with increased mechanical properties while considering a trial on 40 human samples. It was carried out using the 3D printers adopted by the radiology departments of Texas Children's Hospital for patient education and surgical planning with the available resources. Olanda et al. [10] evaluated the efficacy of two 3D-printed NP swab designs (Lattice Swab and Origin KXG) for the diagnosis of COVID-19. A total of 70 adult patients (37 COVID-positive and 33 COVID-negative) underwent RT-PCR testing, with a Flocked swab followed by one or two 3D-printed swabs. It was found that high concordance of 3D-printed nasopharyngeal swabs with the control swab results. It was strongly recommend using 3D-printed NP swabs during the COVID-19 pandemic. This explained the degree of flexibility that 3D printing technology offered in tackling the pandemic. The 3D-printed swabs can also be used to diagnose other common upper respiratory tract pathogens, including respiratory syncytial virus, influenza virus, and Streptococcus pyogenes [8].

1.3. AM/3D-Printed Ventilators and Valves

Severely infected COVID-19 patients need ventilators to support respiration [14]. Approximately 2.4% of COVID-19-infected patients need ventilators to support respiration. A mechanical ventilator supports the patient's respiration by providing positive lung pressure [15]. The first 3D-printed ventilator was developed in Spain [16]. To quicken the design and development process of the ventilators' critical and intricate components is the need of the hour, and the AM technology has the capability to achieve it [16]. Through integrated manufacturing capabilities of additive manufacturing technology, assembly steps required for ventilators can be minimized. With an agenda to develop critical parts for a low-cost ventilator, the University of Minnesota has collaborated with a 3D printing service provider, Protolabs, to develop essential elements for low-cost ventilators [11].

The game-changing idea of splitting a single ventilator for two or more patients has been proven to be an excellent solution for ventilator shortage [17]. A practical study in 2006 by Greg Neyman [18] indicated that ventilator splitters could be used to support the respiration of four patients with a single ventilator. It has been proposed that a single ventilator can be quickly modified to support four individuals of up to 70 kg for a limited time during an alarming situation such as multiple casualties with respiratory failure [18]. Dependency on the conventional injection molding technique for producing the ventilator splitters takes more than a week. Using 3D-printed ventilator splitters, a single ventilator can accommodate multiple patients in life-saving situations, as demonstrated in **Figure 2**. Formlabs and Prisma Heath South Carolina have successfully 3D printed these splitters [11]. The ventilator circuit splitter team [19], a medical professional group in the USA, has designed ventilator splitters and made design files open-access. The ventilator circuit splitter team has also discussed print parameters and verification guidelines after printing, according to which the FDM printer with a nozzle diameter of 0.4 mm, 100% infill, 0.2–0.3 mm layer height, and print direction of upside-down Y-direction for circuit splitters and an upright position for limiters can be used with a biocompatible polymer [19].

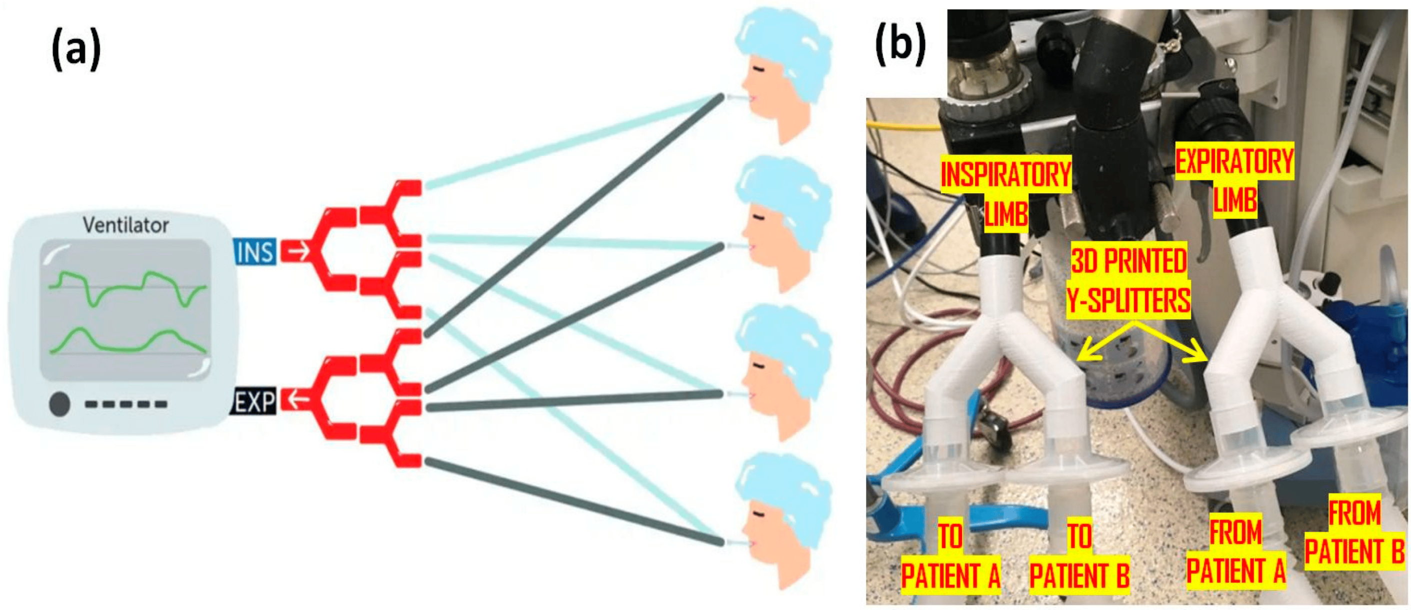

Figure 2. Ventilator splitter: (**a**) schematic representation; (**b**) splitters connected to a shared ventilator [19].

Ventilator valves are the attachments used to deliver oxygen at fixed concentrations for patients with acute respiratory distress, including COVID-19. In 2020, a hospital in Italy with nearly 250 critically ill COVID-19 patients on ventilator support ran out of ventilator valves needed to connect the patients to the machines. Due to the unexpected increase in demand, the original suppliers could not meet the high demand. Isinnova used 3D printing to respond quickly to the situation and successfully printed ventilator valves [19]. Ventilator valves were prototyped in a short time of 8 h, 100 valves were produced in a day, and each valve costed less than EUR 1 [20][21]. Printed ventilator valves have saved lives, displaying the rapid response capabilities of AM. Isinnova produced ventilator valves prioritizing life-and-death situations over copyrights and medical issues, making them unable to share relevant information and design [22] publicly. The FDA's recent (26 August 2022) press note addresses using 3D-printed medical device parts and suggests verifying the 3D-printed products' fit and use before they are used in a clinical setting [23].

AM/3D printing technology was not just limited to addressing the shortage of PPE and other devices during the COVID-19 pandemic. Stephanie et al. [24] have predicted that 3D printing will revolutionize the pharmaceutical industry in drug research, development, and production applicable to the coronavirus. A robust and dynamic drug supply system will be the key to managing future crises. Wen-Kai et al. [25] trust that 3D printing can be used as a decentralized and flexible drug production system with insufficient logistical infrastructure and supply chains. In drug production systems, 3D printing can also be used in disease hot spots with extensive quarantine measures or rural healthcare centers in remote locations [25]. Martin et al. [26] suggested that printing 3D models for planning complex orthopedic, brain, and abdominal tumor surgeries reduces the patients' admission time in the hospital. This, in turn, reduces the risks of intra-hospital COVID-19 infections and the percentage of bed occupancy. The COVID-19 contagion can be controlled by tracking, monitoring, and early intervention at home. Mohammedhusen et al. [27] developed a bracelet prototype to detect biomedical parameters such as low blood oxygenation or high temperature to provide a home-based solution using 3D printing. These biomedical parameters are instrumental in monitoring a patient with a viral infection. This bracelet is proficient in tracking the number of other bracelets in proximity and can be used to monitor a user's in-home quarantine. Using Optomec's Aerosol Jet Technology low-cost printed sensors, researchers at Carnegie Mellon University have developed a device capable of identifying antibodies in 10 to 15 s, and the device is in the trial and testing stage for coronavirus patients [28]. To understand the long-term damage caused by a coronavirus, companies such as Axial3D, Belfast Health, and Social Care Trust have printed lung models. These lung models were prepared using the CT scan data taken on the 14th day of infection and were used to demonstrate the various effects of the virus [28]. A bioprinting company based in San Francisco, Prellis Biologics, explored how synthetic bioprinted lymph nodes can be used to produce fully human COVID-19 antibodies [28]. To reduce the healthcare professionals' risk while swab testing, robotics researchers from the University of Southern Denmark have developed the world's first fully automated robot to carry out throat swab tests for COVID-19 [28]

2. AM/3D Printing in Non-Medical Applications of COVID-19

Direct contact with commonly touched surfaces, such as elevator buttons, door handles, and computer keyboards, can spread viral diseases [29]. In Paris, to lower the risk of COVID-19 contamination by limiting direct contact, François et al. [29] succeeded in printing hands-free door hooks, openers, and button-pushers, which were later dispatched to Greater Paris University Hospitals and other state institutions. Materialise, a 3D printing and software solution firm, developed several hands-free door openers (**Figure 3**) and made these designs available open-source [30].

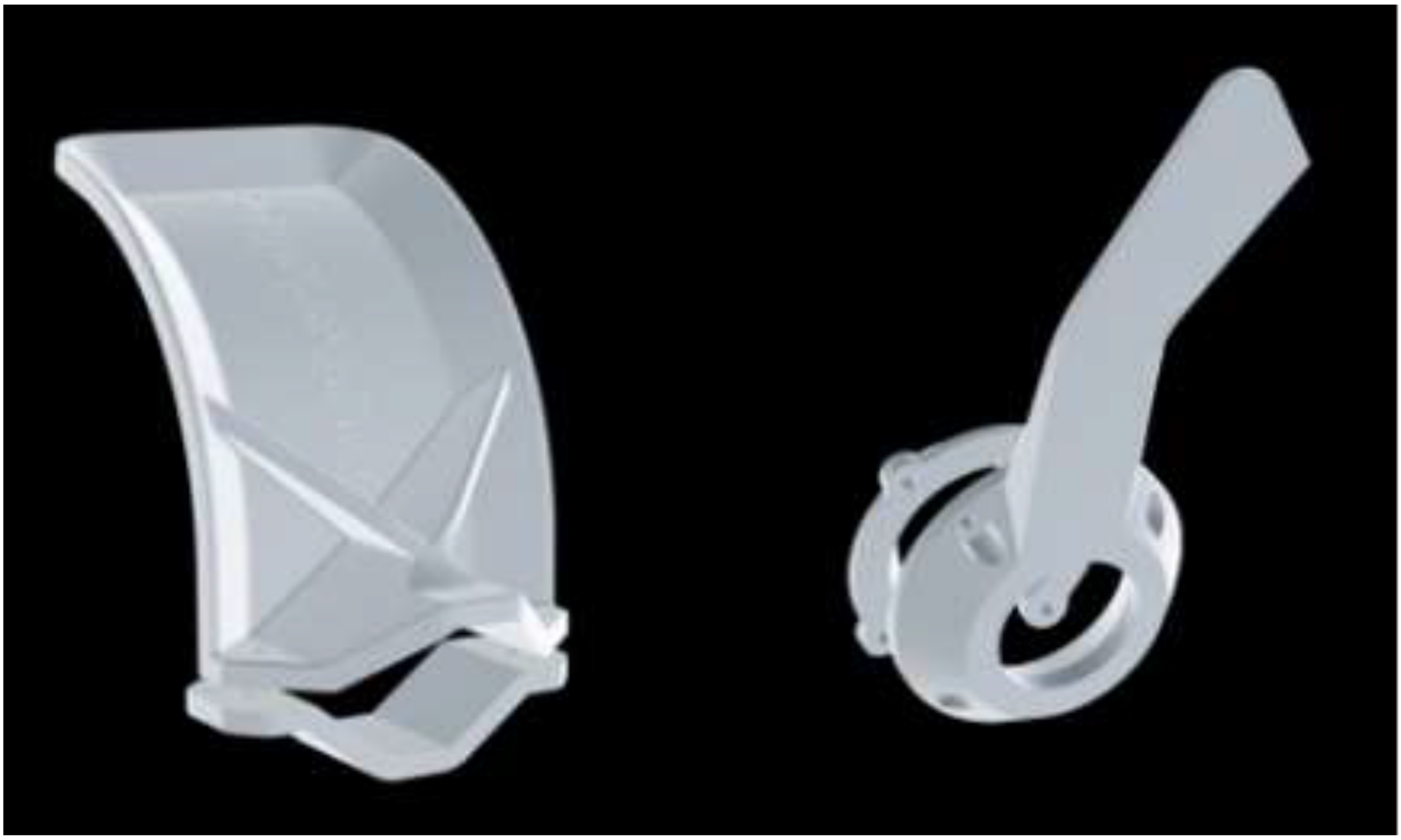

Figure 3. The 3D printable hands-free door opener from Materialise [30].

Thermal scanning using handheld infrared thermometers has been the most common method for thermal screening in public places. Personnel involvement in thermal screening has raised concerns, as there is a possibility of violating the safe distance between two or more people [31]. Abuzairi et al. [31] have printed infrared thermometers using 3D printing and made open-source designs to eliminate human dependency on thermal screening. The developers call this 3D-printed infrared thermometer i-Thermowall, which can be seen in **Figure 4** [31].

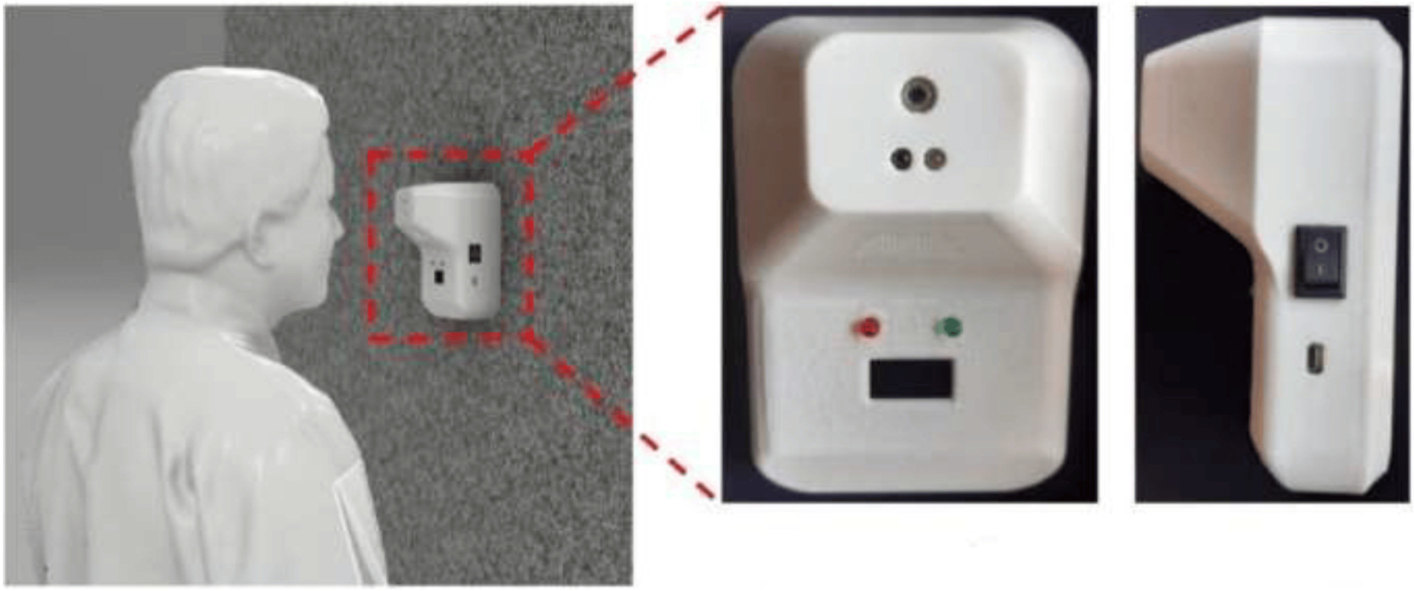

Figure 4. The 3D-printed infrared thermometer (i-Thermowall) [31]; open access.

3. AM/3D Concrete Printing and COVID-19 Pandemic

The construction sector is one of the most significant contributors to the global economy yet has exhibited notably poor productivity compared to other sectors. It has always been a challenge for the global infrastructure and construction industry to meet the ever-increasing global demands [32]. Post-COVID-19 outbreaks, the demand for isolation wards and quarantine shelters skyrocketed; meanwhile, the disordered and disrupted supply chains posed a more significant challenge for the construction sector. Automation in construction technology has gained prime focus in recent years. The recent trends in 3D printing include its advent in construction technology. AM/3D printing using concert and cob (an earth-based material) has proved its superiority over conventional construction methods. The primary advantages are reduced costs and time required for constructing rapid isolation wards or shelters (350 sq. ft. house can be built within a week's time) [33][34][35]. In the pre-COVID era, there were few examples of using 3D printing in the construction of houses and shelters [33]. However, in 2018, a group of IIT Madras faculty members collaborated with a startup company Tvasta to build a 350 sq. ft. house in a week inside the university campus [36]. The same Tvasta team in 2020 made a 600 sq. ft. house inside IIT Madras and assured the ability to build homes in 3 weeks. Tvasta says that the green strength of 3D-printed concrete can be achieved in a few minutes, and the overall structure will be ready in 7–10 days [37].

Nonetheless, the literature reveals that the reduced bonding strength between successive layers, increased deformation layers, and dry-shrinkage issues are some of the challenges to be overcome for a better 3D-printed architecture [33][35]. Very few attempts have been made to develop 3D-printed isolation wards/quarantine shelters for coronavirus patients and medical staff. In February 2020, Winsun, a China-based company, 3D printed isolation wards for COVID-19 patients using concrete and recycled materials, each of the structures measuring 10 square meters in area with a height of 2.8 m. It has been claimed that the units were built according to the standards of even withstanding earthquakes and extreme conditions [38].

References

1. Vordos, N.; Gkika, D.A.; Maliaris, G.; Tilkeridis, K.E.; Antoniou, A.; Bandekas, D.V.; Mitropoulos, A.C. How 3D printing and social media tackles the PPE shortage during COVID-19 pandemic. Saf. Sci. 2020, 130, 104870.
2. U.S. Department of Health and Human Services; Food and Drug Administration; Center for Devices and Radiological Health (CDRH); Office of Product Evaluation and Quality (OPEQ). Enforcement Policy for Telethermographic Systems During the Coronavirus Disease 2019 (COVID-19) Public Health Emergency. In Guidance for Industry and Food and Drug Administration Staff; Food and Drug Administration: Rockville, MD, USA, 2020; Volume 2.
3. Ford Partners with 3M, GE Healthcare to Make Respirators, Ventilators and Face Shields Amid Coronavirus Outbreak. Available online: https://www.detroitnews.com/story/business/autos/ford/2020/03/24/ford-partners-3-m-ge-healthcare-respirators-ventilators-face-shields/2905986001/ (accessed on 8 February 2021).
4. People Are 3D Printing Personal Protective Equipment to Help Hospitals With Shortage: NPR. Available online: https://www.npr.org/local/305/2020/04/01/825217523/people-are-3-d-printing-personal-protective-equipment-to-help-hospitals-with-shortage (accessed on 8 February 2021).
5. Decker, S.J.; Goldstein, T.A.; Ford, J.M.; Teng, M.N.; Pugliese, R.S.; Berry, G.J.; Pettengill, M.; Silbert, S.; Hazelton, T.R.; Wilson, J.W.; et al. 3D Printed Alternative to the Standard Synthetic Flocked Nasopharyngeal Swabs Used for COVID-19 testing. Clin. Infect. Dis. 2020, 73, e3027–e3032.
6. Starosolski, Z.; Admane, P.; Dunn, J.; Kaziny, B.; Huisman, T.A.G.M.; Annapragada, A. Design of 3D-printed nasopharyngeal swabs for children is enabled by radiologic imaging. Am. J. Neuroradiol. 2020, 41, 2345–2347.
7. Bennett, I.; Bulterys, P.L.; Chang, M.; DeSimone, J.M.; Fralick, J.; Herring, M.; Kabaria, H.; Kong, C.S.; Larson, B.; Lu, O.; et al. The rapid deployment of a 3D printed 'Latticed' nasopharyngeal swab for COVID-19 testing made using digital light synthesis. medRxiv 2020.
8. Williams, E.; Bond, K.; Isles, N.; Chong, B.; Johnson, D.; Druce, J.; Hoang, T.; Ballard, S.A.; Hall, V.; Muhi, S.; et al. Pandemic printing: A novel 3D-printed swab for detecting SARS-CoV-2. Med. J. Aust. 2020, 213, 276–279.
9. Gallup, N.; Pringle, A.M.; Oberloier, S.; Tanikella, N.G.; Pearce, J.M. Parametric nasopharyngeal swab for sampling COVID-19 and other respiratory viruses: Open source design, SLA 3-D printing

and UV curing system. HardwareX 2020, 8, e00135.

10. Oland, G.; Garner, O.; de St Maurice, A. Prospective clinical validation of 3D printed nasopharyngeal swabs for diagnosis of COVID-19. Diagn. Microbiol. Infect. Dis. 2021, 99, 115257.
11. 8 Ways 3D Printing is Helping to Fight Coronavirus—ASME. Available online: https://www.asme.org/topics-resources/content/8-ways-3d-printing-is-helping-to-fight-coronavirus (accessed on 8 February 2021).
12. 3D Printed COVID-19 Test Swabs|Formlabs. Available online: https://formlabs.com/asia/covid-19-response/covid-test-swabs/ (accessed on 8 February 2021).
13. Alyouha, S.; Almazeedi, S.; Alghounaim, M.; Al-Mutawa, Y.; Alsabah, S. Polyester tipped 3-dimensionally printed swab that costs less than US$0.05 and can easily and rapidly be mass produced. BMJ Innov. 2020, 6, 262–264.
14. Lyengar, K.; Bahl, S.; Vaishya, R.; Vaish, A. Challenges and solutions in meeting up the urgent requirement of ventilators for COVID-19 patients. Diabetes Metab. Syndr. Clin. Res. Rev. 2020, 14, 499–501.
15. Advincula, R.C.; Dizon, J.R.C.; Chen, Q.; Niu, I.; Chung, J.; Kilpatrick, L.; Newman, R. Additive manufacturing for COVID-19: Devices, materials, prospects, and challenges. MRS Commun. 2020, 10, 413–427.
16. Rowan, N.J.; Laffey, J.G. Challenges and solutions for addressing critical shortage of supply chain for personal and protective equipment (PPE) arising from Coronavirus disease (COVID19) pandemic—Case study from the Republic of Ireland. Sci. Total Environ. 2020, 725, 138532.
17. Tino, R.; Moore, R.; Antoline, S.; Ravi, P.; Wake, N.; Ionita, C.N.; Morris, J.M.; Decker, S.J.; Sheikh, A.; Rybicki, F.J.; et al. COVID-19 and the role of 3D printing in medicine. 3D Print. Med. 2020, 6, 11.
18. Neyman, G.; Irvin, C.B. A Single Ventilator for Multiple Simulated Patients to Meet Disaster Surge. Acad. Emerg. Med. 2006, 13, 1246–1249.
19. ventsplitter.org—Free 3D Printable Ventilator Circuit Splitter. Available online: http://ventsplitter.org/ (accessed on 8 February 2021).
20. Coronavirus: 3D Printers Save Hospital with Valves—BBC News. Available online: https://www.bbc.com/news/technology-51911070 (accessed on 8 February 2021).
21. Meet The Italian Engineers 3D-Printing Respirator Parts For Free To Help Keep Coronavirus Patients Alive. Available online: https://www.forbes.com/sites/amyfeldman/2020/03/19/talking-with-the-italian-engineers-who-3d-printed-respirator-parts-for-hospitals-with-coronavirus-patients-for-free/?sh=277a072778f1 (accessed on 8 February 2021).

22. Viera-Artiles, J.; Valdiande, J.J. 3D-printable headlight face shield adapter. Personal protective equipment in the COVID-19 era. Am. J. Otolaryngol.—Head Neck Med. Surg. 2020, 41, 102576.
23. 3D Printing of Medical Devices, Accessories, Components, and Parts during the COVID-19 Pandemic|FDA. Available online: https://www.fda.gov/medical-devices/coronavirus-covid-19-and-medical-devices/3d-printing-medical-devices-accessories-components-and-parts-during-covid-19-pandemic (accessed on 20 September 2022).
24. WHO Director-General's opening remarks at the media briefing on COVID-19—11 March 2020. Available online: https://www.who.int/director-general/speeches/detail/who-director-general-s-opening-remarks-at-the-media-briefing-on-covid-19---11-march-2020 (accessed on 7 February 2021).
25. Hsiao, W.K.; Lorber, B.; Paudel, A. Can 3D printing of oral drugs help fight the current COVID-19 pandemic (and similar crisis in the future)? Expert Opin. Drug Deliv. 2020, 17, 899–902.
26. Martin-Noguerol, T.; Paulano-Godino, F.; Menias, C.O.; Luna, A. Lessons learned from COVID-19 and 3D printing. Am. J. Emerg. Med. 2020, 46, 659–660.
27. Manekiya, M.; Donelli, M. Monitoring the COVID-19 diffusion by combining wearable biosensors and smartphones. Prog. Electromagn. Res. M 2021, 100, 13–21.
28. Additive manufacturing and coronavirus 3D Printing Media Network—The Pulse of the AM Industry. Available online: https://www.3dprintingmedia.network/category/industry-2/additive-manufacturing-and-coronavirus/ (accessed on 7 February 2021).
29. François, P.M.; Bonnet, X.; Kosior, J.; Adam, J.; Khonsari, R.H. 3D-printed contact-free devices designed and dispatched against the COVID-19 pandemic: The 3D COVID initiative. J. Stomatol. Oral Maxillofac. Surg. 2021, 122, 381–385.
30. Hands-Free Door Opener: Technical Information—Materialise. Available online: https://www.materialise.com/en/hands-free-door-opener/technical-information (accessed on 8 February 2021).
31. Abuzairi, T.; Sumantri, N.I.; Irfan, A.; Mohamad, R.M. Infrared thermometer on the wall (iThermowall): An open source and 3-D print infrared thermometer for fever screening. HardwareX 2021, 9, e00168.
32. Sanjayan, J.G.; Nematollahi, B. 3D Concrete Printing for Construction Applications; Elsevier Inc.: Amsterdam, The Netherlands, 2019.
33. Siddika, A.; al Mamun, M.A.; Ferdous, W.; Saha, A.K.; Alyousef, R. 3D-printed concrete: Applications, performance, and challenges. J. Sustain. Cem. Mater. 2020, 9, 127–164.
34. Alhumayani, H.; Gomaa, M.; Soebarto, V.; Jabi, W. Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete. J. Clean. Prod. 2020,

270, 122463.

35. Nair, A.; Aditya, S.D.; Adarsh, R.N.; Nandan, M.; Dharek, M.S.; Sreedhara, B.M.; Prashant, S.C.; Sreekeshava, K.S. Additive Manufacturing of Concrete: Challenges and opportunities. IOP Conf. Ser. Mater. Sci. Eng. 2020, 814, 012022.
36. Chennai: 350 Sqft House Can Be Built in Week at Low Cost. Available online: https://www.deccanchronicle.com/nation/current-affairs/251018/chennai-350-sqft-house-can-be-built-in-week-at-low-cost.html (accessed on 9 February 2021).
37. This Startup Will Build Your House in Three Weeks at Half the Cost—Times of India. Available online: https://timesofindia.indiatimes.com/companies/this-startup-will-build-your-house-in-three-weeks-at-half-the-cost/articleshow/79614197.cms (accessed on 9 February 2021).
38. WinSun Deploys 3D Printed Isolation Wards for Coronavirus Medical Staff » 3D Printing Media Network—The Pulse of the AM Industry. Available online: https://www.3dprintingmedia.network/winsun-3d-printed-isolation-wards-coronavirus-medical-workers/ (accessed on 9 February 2021).