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Review

Applications of additive manufacturing (AM) in sustainable energy generation and battle against COVID-19 pandemic: The knowledge evolution of 3D printing

Yanen Wang [a,*,1], Ammar Ahmed [a,1], Ali Azam [b], Du Bing [c,**], Zhang Shan [a,**], Zutao Zhang [b,**], Muhammad Kashif Tariq [d], Jakiya Sultana [a], Ray Tahir Mushtaq [a], Asad Mehboob [e], Chen Xiaohu [a], Mudassar Rehman [a]

[a] *Department of Industry Engineering, Northwestern Polytechnical University, Xi'an, 710072, PR China*
[b] *School of Mechanical Engineering, Southwest Jiaotong University, Chengdu, 610031, PR China*
[c] *Center of Stomatology, The Second People's Hospital of Foshan, Foshan, 528000, PR China*
[d] *Department of Mechanical Engineering, University of Engineering & Technology, Lahore, 54890, Pakistan*
[e] *Department of Material Science and Engineering, Northwestern Polytechnical University, Xi'an, 710072, PR China*

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ABSTRACT

Sustainable and cleaner manufacturing systems have found broad applications in industrial processes, especially aerospace, automotive and power generation. Conventional manufacturing methods are highly unsustainable regarding carbon emissions, energy consumption, material wastage, costly shipment and complex supply management. Besides, during global COVID-19 pandemic, advanced fabrication and management strategies were extremely required to fulfill the shortfall of basic and medical emergency supplies. Three-dimensional printing (3DP) reduces global energy consumption and CO_2 emissions related to industrial manufacturing. Various renewable energy harvesting mechanisms utilizing solar, wind, tidal and human potential have been fabricated through additive manufacturing. 3D printing aided the manufacturing companies in combating the deficiencies of medical healthcare devices for patients and professionals globally. In this regard, 3D printed medical face shields, respiratory masks, personal protective equipment, PLA-based recyclable air filtration masks, additively manufactured ideal tissue models and new information technology (IT) based rapid manufacturing are some significant contributions of 3DP. Furthermore, a bibliometric study of 3D printing research was conducted in CiteSpace. The most influential keywords and latest research frontiers were found and the 3DP knowledge was categorized into 10 diverse research themes. The potential challenges incurred by AM industry during the pandemic were categorized in terms of design, safety, manufacturing, certification and legal issues. Significantly, this study highlights the versatile role of 3DP in battle against COVID-19 pandemic and provides up-to-date research frontiers, leading the readers to focus on the current hurdles encountered by AM industry, henceforth conduct further investigations to enhance 3DP technology.

1. Introduction

The availability of primary requirements such as energy, products, and services to everyone is inevitable for an enhanced lifestyle in the modern era. The robust development of new industries, manufacturing technologies, and sustainable power generation methods made it achievable. However, various troubles are triggered for the echo system and living organisms. The global primary energy consumption will rise to 11.6 times in 2050 compared to 1950 [1]. Non-renewable manufacturing processes and energy sources cause hazardous environmental effects, i.e., CO_2 and greenhouse gases (GHGs), posing severe threats to human health. Industrial processes such as conventional

* Corresponding author.
** Co-Corresponding authors.
E-mail addresses: wangyanen@126.com (Y. Wang), ammartahir@uet.edu.pk (A. Ahmed), aliazam@uet.edu.pk (A. Azam), 93881976@qq.com (D. Bing), zzt@swjtu.edu.cn (Z. Zhang).
[1] Ammar Ahmed has participated equally in the manuscript so he should be considered as Co-first author.

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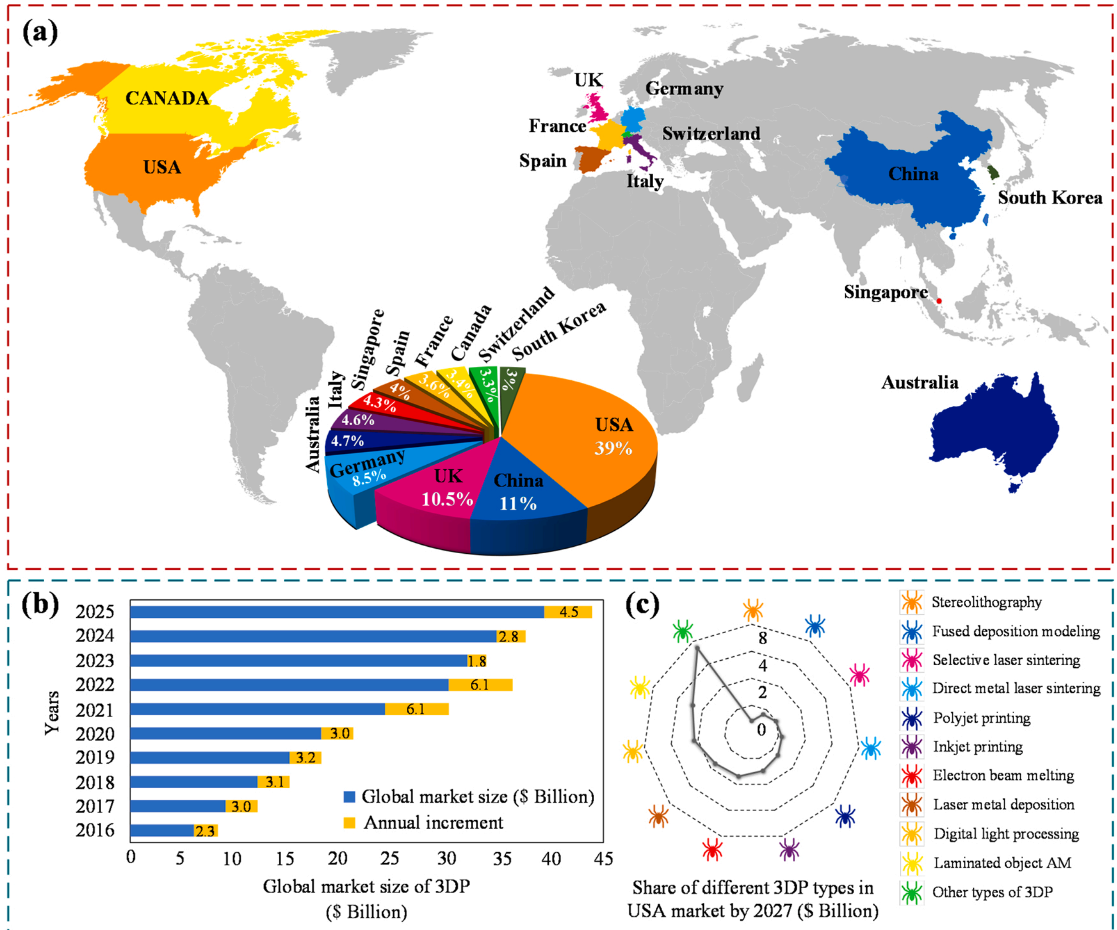

Fig. 1. (a) The most prolific countries involved in the advancement of 3D printing research (b) Annual progress in the 3D printing global market in billion US dollars [11] (c) Estimated share of various types of additive manufacturing in the overall USA 3D printing market by 2027.

manufacturing, mass production, testing, maintenance, and waste disposal are responsible for consuming 22 % of the total energy [2] and producing approximately 20 % of the global CO_2 emissions [3]. According to a survey of the World Commission on Environment and Development [4], the industrial sectors such as aerospace, automotive, and energy generation are required to develop sustainable production and utilization techniques. This demands a shift towards efficient manufacturing and energy production strategies, resulting in minimum material wastage, greenhouse gas emissions (GHGs), exploitation of natural resources, and disturbances in ecosystems [5,6]. A substantially influential manufacturing technology realizing the motive has emerged as additive manufacturing (AM) or 3-dimensional printing (3DP).

3D printing is widely being used to manufacture household, industrial and commercial products and fabricate various renewable and sustainable energy harvesting mechanisms [7]. The conventional manufacturing techniques such as milling, shaping, CNC lathe operations, and casting are attributed with some disadvantages, including material wastage, residual stresses, lower degree of automation, high expertise, expensive machining, level of complexity [8], huge supply chains and inventories, design immovability, lower customization, shipping, and enhanced carbon emissions [9]. 3DP-based manufacturing significantly eliminates these problems, enabling the application of biodegradable and reusable materials for fabrication [7]. According to a study, using 3DP instead of conventional manufacturing, the intensities of the energy consumption and CO_2 emissions due to industrial manufacturing can be reduced by maximally 5% by 2025 [10].

The efforts of various countries in enhancing 3-dimensional printing technology are shown in Fig. 1(a). It can be noticed that the USA was the leading contributor in 2020, holding about 39 % of the total publications related to 3DP research, followed by China with an 11 % share. Fig. 1(b) shows the annual progress rate of the global market of 3D printing. According to an estimation, the global 3DP market will be valued at about USD 40 billion by 2025. Moreover, various categories of 3D printing are expected to share almost above USD 7 billion in the overall 3DP market of the USA by 2027 (Fig. 1(c)). Globally, more than 1.5 million 3D printers were distributed in 2019 and the number is likely to arrive at about 8 million by 2027 [11]. This is due to the increasing rapid prototyping and strong research and development (R & R&D) in 3DP.

During the COVID-19 pandemic, the supply chains of basic and emergency goods, including medical health care devices, personal protective equipment, raw materials, and food, were disrupted, causing an increased demand for medical and health equipment. Meanwhile, where conventional manufacturing techniques were affected by lockdowns and restricted transportation, the rapid prototyping and digital adaptability of 3DP enabled the rapid mobilization of the technology as an effective response to the emergency. Despite abrupt interruptions in production and supply chains, certain parts could be produced on-demand by any regionalized 3D printing service by online sharing of the CAD designs. Furthermore, the additive nature of 3DP provides easy customization of complex designs. The wide applications of 3DP during the COVID-19 pandemic are emergency dwellings [12], personal protective equipment (PPE) [13], and medical devices, visualization aids, and personal safety gadgets.

Nazir et al. [14] analyzed the potential of 3D printing with smart CAD design to overcome shortfalls of basic and emergency supplies during COVID-19. Moreover, the critical research gaps needing further

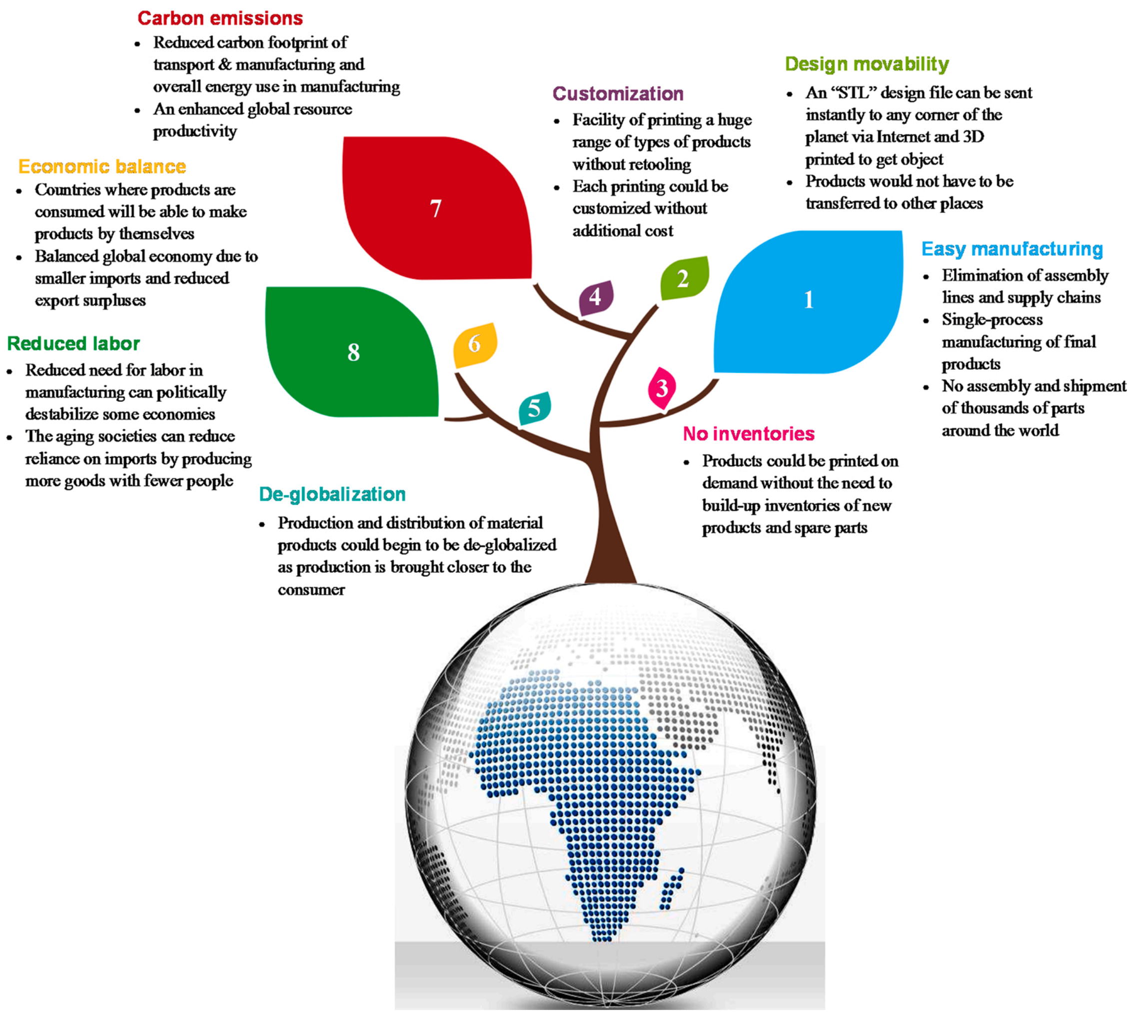

Fig. 2. Advantages of 3D printing over subtractive manufacturing.

research to utilize the full potential of 3DP in emergencies were discussed. Andres et al. [15] analyzed a three-panel foldable facepiece respirator. After experimental testing of the performance and assembly process, the facepiece respirator design was certified against the EN149 standard for a Belgian hospital during the COVID-19 pandemic. This development procedure of a respirator mask, including the shape/design of the respirator, material selection, processing, nose bridge, welding of panels, sealing foam for nose frame, packaging, exhaust valve, and elastic components for harnessing, was chronologically demonstrated to achieve minimum viable product and upscaled production within four weeks.

Patel et al. [16] conducted a case study for additive manufacturing applications against the COVID-19 pandemic, including the 3D printing supply chain and market trends in India. Some potential applications of 3DP in the battle against the COVID-19 pandemic were 3D-printed face shields, stopgap face masks, mask adjusters, diagnostic swabs, ventilator parts, hands-free door opener, and quarantine booths. Moreover, the utilization of drone technology was demonstrated for surveillance, lockdown enforcement, body temperature monitoring, public broadcast, disinfectants spraying [17], basic and medical emergency supplies delivery [18], surveying, and mapping [19]. Tareq et al. [20] determined the potential of 3D printing for applications against COVID-19 such as ventilator valves, face shields, face masks, and nasopharyngeal swabs by analyzing the major contributions of the AM industry, researchers, academics, individuals, and users.

Malik et al. [21] studied the possibility of human-robot integrated manufacturing of ventilator parts for COVID-19 patients to fulfill the emergency demands. It was demonstrated that human-robot collaborative manufacturing could reduce direct person-hours, total production time, and facilitates faster integration, safe companionship of humans for social distancing, and diversity of applications after emergency vanishes. In another study [22], efforts were made to develop a 3D printed respirator to fulfill the medical emergency demands by analyzing particle transmission to improve filtration efficiency. The respiratory masks were fabricated with various materials, configurations, and 3DP processes. The additively manufactured respirators achieved an efficiency of approx. 90 % with a particle filtration range of 100−300 nm, and the filtration performance was comparable to N-95 masks. Some other significant contributions from additive manufacturing industries are 3D printed medical face shields [23], additively manufactured respiratory protective equipment from emulsion inks [24], PLA-based biodegradable masks [25], bioprinted ideal tissue platform for COVID research [26], and new information technology (IT) based rapid manufacturing [27] in battle against COVID-19 pandemic. Ammar et al. highlighted the critical frontiers, hotspots and research gaps in the 3D printing technology for COVID-19 related applications [28].

Many 3D printing companies in Europe and the USA offered their inhouse facilities to fulfil the shortage of medical equipment such as 3D-printed door openers, face shields, respiratory masks, quarantine booths, ventilator parts, hand sanitizer holders around the world. Besides, Airbus, BMW, Ferrari, Nissan, and Volkswagen have also used their 3D printing facilities to manufacture medical devices [29,30]. The most prolific 3D printing services contributing in the mission are

Fig. 3. Schematic, classification, functional materials, and applications of 3D printing.

Stratasys [31], Prusa [32], Thingiverse [33], Issinova [29,34], and Formlabs [35]. Furthermore, artificial intelligence, Big Data, Internet of Things, mathematical modeling, nanotechnology, telemedicine, and robotics have played crucial role in predictions, community screening, diagnostics, treatment and vaccine development [36].

3D printing has also found various applications in other domains, including aerospace, construction, food industry, automotive [37], soft robotics [38], biomedical sciences, health care, prosthetic implants [39, 40], printed electronics [41], biomimetic designs [42], energy harvesting systems, water treatment and desalination [43]. Several studies have been conducted recently regarding printer design, printable materials [37,44], control parameters [45,46], biomimicry [47], classifications [48,49], mechanical and thermal properties, fatigue life, stability [50, 51], printing speed [52], productivity, energy harvesting [53], potential challenges [37,54], and environmental and economic impact assessment [55]. However, the role of additive manufacturing in developing emergency supplies against the COVID-19 pandemic and intellectual background of the 3DP-related research is rarely discussed in depth to determine research frontiers and detailed knowledge structure of 3DP. Moreover, the AM has also found vast applications in developing sustainable energy generation systems that need to be discussed. The bibliometric or scientometric investigation facilitates the determination of the recent developments, research frontiers, hot spots, and the structure of knowledge, which can significantly help the researchers to focus on the most critical aspects of the technology.

In this research paper, the applications of 3D printing in the battle against the COVID-19 pandemic is comprehensively discussed, and the sustainability aspects of 3DP are briefly summarized by considering its impact on global energy consumption and CO_2 emissions. The applications of 3D printing related to sustainable and renewable energy harvesting mechanisms and the techno-socio-economic and environmental impacts of 3DP were also highlighted briefly. Various energy generation devices used to harvest renewable energy from the ocean, wind, human and ambient environment were reported to be fabricated through 3DP.

Table 1
Categorization, benefits, drawbacks, and various applications of 3D printing.

Sr.	Category	Materials	Advantages	Disadvantages	Applications
1	Binder jetting	Metals, polymers, ceramics, composites [63]	Cheaper, faster	Poor surface finish and strength	Molds, cores, acoustics, porous components, lightweight structures, electrodes, antennas, surgical implants, denture frameworks, and filters [63]
2	Material extrusion	Metal pastes, Thermoplastic polymers, composites [64,69]	Cheaper, fully functional, multi-colored printing	Vertically anisotropic products will have stepped surface	Electrically conductive structures, Fiber-based composites for aircrafts Automotives, biosensors, and nasal prosthesis [64]
3	Directed energy deposition	Hybrids, Metals, [65]	Strong, high-quality parts, multi-DOF nozzle, used for repairing	The surface finish is not good at higher printing speeds	Cardiovascular devices, Orthopedics, dental implants, Welding, cladding, gas-turbine blade repairing, aero-engine parts of Ti-6Al-4 V alloy [65]
4	Material jetting	Ceramics, Polymers, composites, hybrid [37,60]	Excellent surface finish, multi-material printing, and good accuracy	Need for supports, limited materials	Concrete, biochemical, medical, biological, and purposes [66,67]
5	Powder bed fusion	Ceramics, Metals, composites, glass polymers, nylon, hybrids [37,68,69]	Excellent accuracy, high speed, no need for support	Poor surface finish, expensive, limited part size, high power consumption	Marine, Aerospace, construction, automobile, food/ jewelry, and heat exchangers [68,69]
6	Sheet lamination	Metals, Polymers, metal-filled tapes paper, ceramics [61,69]	Color printing, cheap, recyclable, bigger printing volume	Limited materials, strength is compromised with adhesive quantity	Reinforced composites, preceramic tapes, lightweight heating elements, printed electronics, and filters for soot particles [61]
7	Vat Photopolymerization	Ceramics, Photopolymers, semi-flexible substances, ABS [69]	High surface finish, fine resolution, and good accuracy	Costly, poor mechanical characteristics, limited materials	Biomedicine, water-resistant materials, and patterns for investment casting [69]

Table 2
Impact of 3D printing on total energy supply and CO_2 emissions in the world expected till 2025 [10].

Sustainability parameter	Overall reduction due to 3DP (over the entire life cycle)	Reduction in lifecycle phases	Involved markets	Highly influenced sectors (% reduction)
Total primary energy supply (TPES)	2.54–9.30 exajoule (EJ)	Production (∼33%)	Consumer products, aerospace industry, medical components, tooling	Aerospace fuels (9–35 %), aerospace manufacturing (8–19 %), medical equipment (5–19 %), tools (3–10 %)
		Utilization (55–60 %)	Aerospace energy demands	
		Discharging (8%)	Aerospace production	
CO_2 emissions	130.5–525.5 metric tons (Mt)	Production (∼25%)	Consumer products, medical equipment, Tooling	Aerospace fuels (9–35 %), aerospace manufacturing (8–19 %), medical equipment (5–19 %), tools (3–10 %)
		Utilization (∼66%)	Aviation (owing to lightweight designs)	
		Discharging (8%)	Consumer goods, fuel burnt, food products	

Furthermore, a bibliometric study of the 3D printing research (published between 1986 and 2021) was conducted to evaluate the research advancements, state-of-the-art knowledge structure, and frontiers for future research in 3DP. The research papers were collected from Science Citation Index Expanded and Emerging Science Citation Index databases, and simulations were run in CiteSpace to attain the following goals.

(a) To find the most influential keywords in the development of 3D printing
(b) Categorization of 3DP based knowledge into knowledge clusters
(c) To evaluate the state-of-the-art knowledge structure and knowledge base of 3DP
(d) To highlight the research frontiers and hotspots in the field of 3DP to help the researchers for future studies

2. Three-dimensional printing (3DP)

Originally, the 3DP technology was developed by Charles Hull in 1986 [54], previously known as stereolithography (SLA), which afterwards evolved in various forms. Technically, 3D printing is defined as a "process of joining materials to make parts from 3D CAD model data, generally layer upon layer, instead of subtractive manufacturing and formative manufacturing methodologies". The benefits of additive manufacturing (AM) over subtractive manufacturing are presented in Fig. 2.

The process of 3D printing and the classification, applications, and usable materials for each category, are shown in Fig. 3. The process starts with a 3D CAD model of the object. Slicing software is used to make cross-sectional layers of the model, saved as a computer file, and sent to the 3D printer. The 3D printer then fabricates the object by spreading each layer through selective placement of material. This is just like an inkjet printer, adding different layers of material on the top of each other to create 3D prints. According to ASTM F2792 standard, AM is categorized into the following types, (i) binder jetting, (ii) Material extrusion, (iii) directed energy deposition (DED), (iv) inkjet 3D printing, (v) powder bed fusion (PBF), (vi) laminated object manufacturing (LOM) and (vii) vat-photopolymerization.

In material extrusion, the material is heated to convert it into a semi-solid state extruded onto the printing bed. It facilitates easy insertion and removal of the filler material [56]. In binder jetting, a jet is used to spread the binding solution layer on the powdered material. Multiple slices of powder and binder are made consecutively to achieve the final printed part [57]. In DED, a laser or electron beam is used to melt the materials spread on the platform using a multi-DOF nozzle to disperse the solvent [58]. In powder bed fusion, the powdered composite material, metal, polymer, or ceramic, is melted through a laser or electron beam. The molten material is solidified to get the final part [59]. In Material Jetting, a jet or nozzle (also called printhead) is used to develop the coatings of a liquid photoreactive material onto the printing bed. The

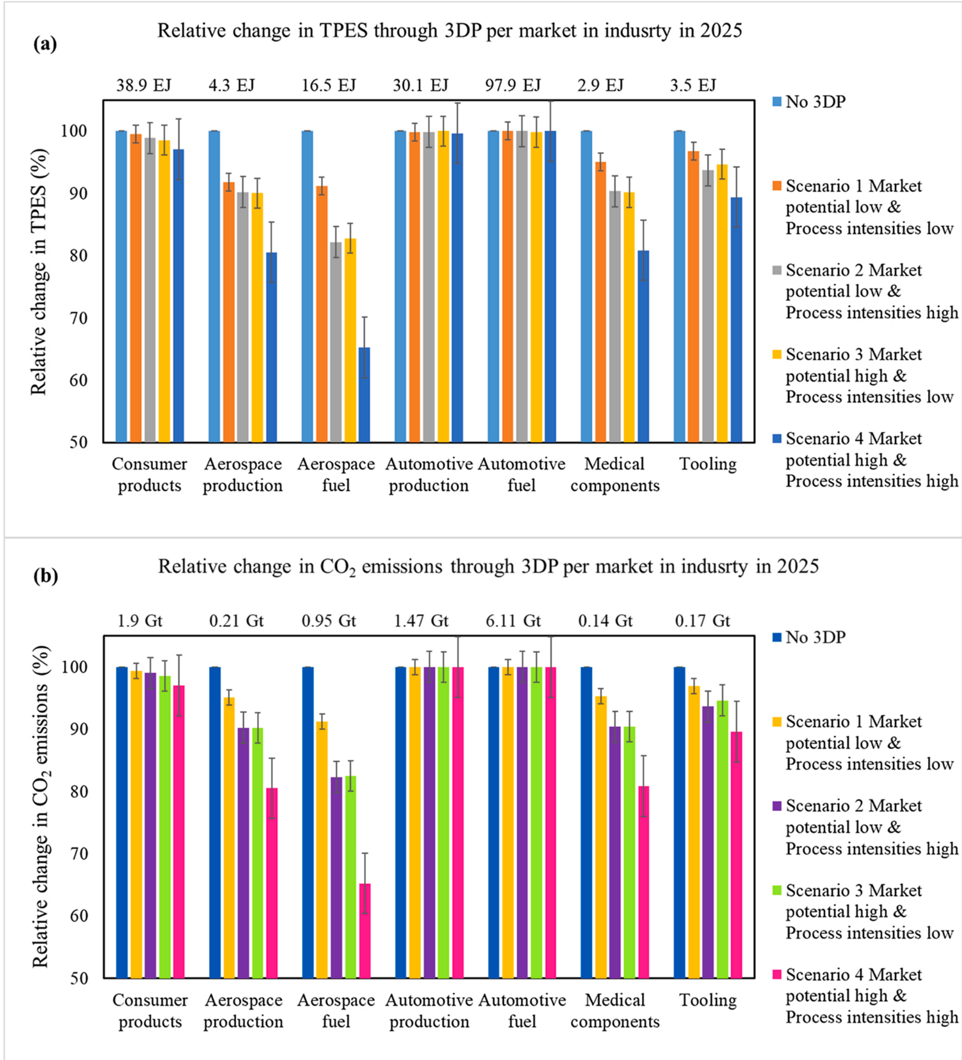

Fig. 4. Impact of 3DP on the total primary energy supply (TPES) and CO_2 emissions: (a) reduction in TPES and (b) reduction in CO_2 emissions with 3DP (re-used with the permission of Elsevier, License No. 4954690016004) [10].

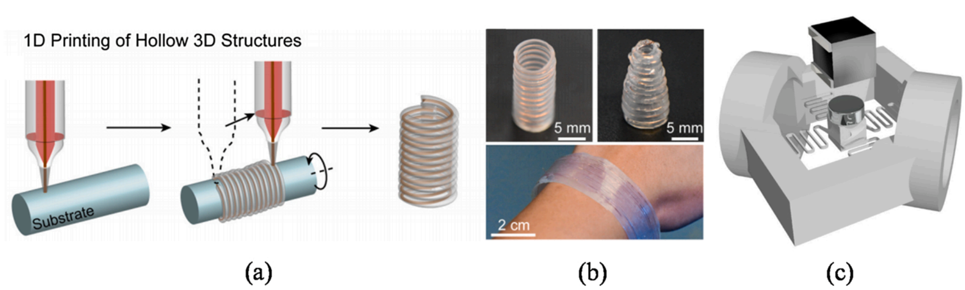

Fig. 5. Applications of 3DP in energy harvesting (a) micro-extrusion of silicone-Cu fibres for triboelectric energy harvester (b) scalability of triboelectric TENG-based wristbands [73] (c) A 3D-printed vibrational energy harvester with assembled magnet coupled with one miniature coil [53].

liquid exposed to ultraviolet rays is cured slowly [60]. In LOM, thin aluminum foils or planar filaments are cut by lasers or blades and joined together to make the product [61]. In Vat photopolymerization, the process of photopolymerization is employed to develop the patterns, models, or prototypes. Underexposure of light, the chemical monomers and oligomers are cross-linked, and a solidified part is obtained [62]. A comprehensive summary of the various types of 3DP in terms of materials, advantages, disadvantages, and applications is provided in Table 1.

As shown in Fig. 3, some conventional and advanced applications of 3DP are presented. Binder jetting is commonly used to make molds, porous components, cores, acoustics, electrodes, antennas, lightweight structures, filters, surgical implants, and denture frameworks [63]. The fused deposition modeling (FDM) is used to develop fiber-reinforced composite structures for aircrafts/automotive, electrically conductive components, biosensors, and nasal prostheses [64]. Some potential applications of directed energy deposition (DED) include orthopedic and dental implants, cardiovascular systems, welding, cladding, gas-turbine blades repairing, 4-stroke engine pistons, and aero-engine parts [65].

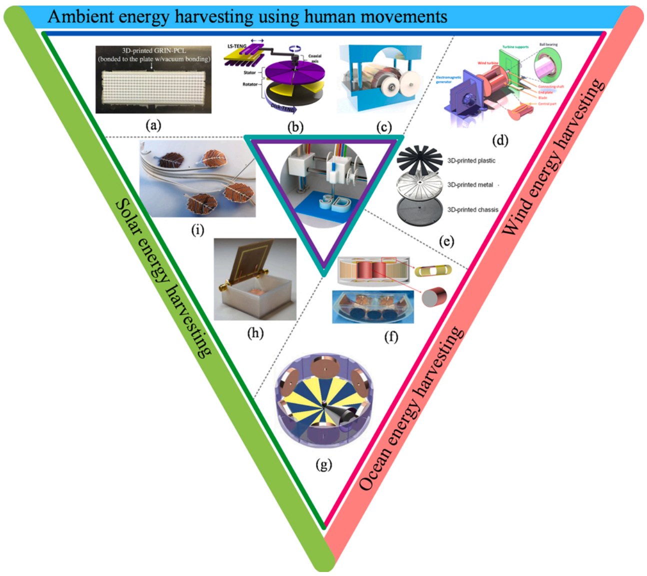

Fig. 6. Applications of 3DP in sustainable energy generation (a) 3D-printed phononic crystal lens for elastic wave energy harvesting (b) 3D-printed hybrid coaxial TENG inspired by a crank engine (HC-TENG) (c) Bidirectional gear transmission-based TENG fabricated through 3D printing (d) 3D printed miniature electromagnetic energy harvesters driven by airflow (e) All 3D printed grating disk type TENG (f) ship-shaped hybridized nanogenerator (SHNG) (g) triboelectric-electromagnetic rotating gyro structured blue energy harvester, All the devices are fabricated using 3D printed parts (h) Solar energy harvester with a 3-D printed package (i) 3D printed solar energy trees (Image credits: alternative-energy-news.info/) (Images are re-used with the permission of Elsevier).[4]

Inkjet or material jetting 3D printing has been widely used to develop construction applications, cementitious concrete, biological, biochemical, and medical products [66,67]. PBF is majorly used in applications related to automobile, heat exchangers, aerospace, marine construction, jewelry/food industries, and oil refineries [68,69]. Laminated object manufacturing (LOM) is used to make reinforced composites, preceramic tapes, lightweight heating elements, printed electronics, and filters for soot particles [61]. Stereolithography (SL) is known for applications related to biomedicine, water-resistant materials, and patterns for investment casting [69].

3. 3DP is a low-waste & low-carbon technology

Industrial processes such as conventional manufacturing, mass production, testing, maintenance, and waste disposal are responsible for consuming 22 % of the total energy supply [70] and producing approximately 20 % of the global CO_2 emissions [3,71]. According to the report published by World Commission on Environment and Development [4], the industries such as aerospace, power generation, and automotive are needed to develop sustainable technologies. This demands a shift towards efficient manufacturing techniques, with minimized material wastage, greenhouse gas emissions (GHGs), exploitation of natural resources, and disturbances in ecosystems [72].

3.1. Energy consumption and CO_2 emissions-based sustainability of 3DP

M. Gebler et al. [10] conducted a state-of-the-art study to determine the impact of 3D printing on the total primary energy supply (TPES) and CO_2 emissions by considering the entire life cycle of the product for a number of industrial sectors, including aerospace, automotive, tooling, consumer products, fuels, and medical devices. In the study, three critical phases of the product lifecycle such as production, utilization and discharging were investigated under four different combinations of market potential and process intensities over a time span of 2013–2025. The important sustainability-based implications and the overall impact of 3DP on the world's total energy supply and CO_2 emissions are described in Table 2.

It was observed that Additive manufacturing can reduce the overall total primary energy consumption and CO_2 emissions over the entire life cycle of a product for all the markets under consideration. The influence of 3DP on the energy supply and CO_2 emissions for different markets including aerospace, automotive, tooling, consumer products, fuels and medical devices, is shown in Fig. 4 [10]. It can be observed that aerospace fuel demands, aerospace production, medical devices and tooling showed a higher reduction in the total energy supply and CO_2 concentrations, with a percentage decrease of 9–35 %, 8–19 %, 5–19 % and 3–10 % respectively, in 2025.

3.2. Applications of 3DP in sustainable energy generation

Renewable energy harvesting, a sustainable application of 3D printing, involves harnessing of useful ambient energy from various sources such as ocean waves, wind flow, sunlight, human movements and mechanical vibrations [5]. A 3D printed stretchable fibre-based triboelectric Nano-generator [73] is shown in Fig. 5(a) and (b), where a metallic wire (usually copper or aluminum) is encapsulated inside the polymeric substance (silica in this case) to make a bracelet that can be used to wear in hand. Human body and metallic wire act like negative and positive electrodes, respectively, and transfer electrons between each other when the bracelet and skin come in and out of contact with each other. Both metallic wire and polymeric cladding possess different electronegativity and work on the principle of static charges and tribo-electrification to harvest energy from the movement of human wrist. In this way, an AC current is produced which can be converted into DC voltage and used to operate the self-powered sensors or health monitoring devices. Similarly a vibrational-electromagnetic energy harvester made by inkjet 3D printing [53] is shown in Fig. 5(c), that uses the kinetic energy of vibrations to move the coil relative to the fixed magnets to generate power.

3D printing is widely being used to develop novel mechanisms of sustainable energy generation. Several devices have been reported to be fabricated using 3D printed parts to harvest energy from human activities and joint movements, wind [74], ocean waves, sound [75], rain droplets and other ambient energy sources [76]. The triboelectric nano-generator (TENG) and piezoelectric nano-generator (PENG) based energy harvesting devices can be easily fabricated using 3D printed substrates, structures, blades [77], rotors or casings. Moreover, biodegradable and reusable materials can be used for manufacturing, due to which fabrication and installation of the energy generation systems have become sustainable. Moreover, the portability of the small-scaled 3D-printed mechanisms is another advantage that has revolutionized the concept of nano- and instant energy generation. Some real-time energy harvesting mechanisms fabricated through 3D printing are shown in Fig. 6. Furthermore, the output energy capacities and applications of some 3D printed energy harvesting devices are enlisted in Table 3.

3.3. Techno-economic, social and ecological aspects of 3D printing

3D printing is more than a technological achievement that revolutionized industrial and manufacturing engineering and influenced many other aspects of life. From jewellery and household decorative articles to highly commercial applications, a wide range of 3DP applicability has empowered the people worldwide to learn to self-sustain. In almost every field of life, 3D printing is being used to develop novel and advanced solutions for technical, social, economic and ecological challenges. Some of the interesting aspects of additive manufacturing are enlisted in Table 4.

Table 3
Output energy capacities and applications of 3D-printed energy harvesting devices[a].

Sr.	Energy device	Source of excitation	Excitations	3DP materials	Output	Applications
1	Wrist-wearable hybridized EMG-TENG	Human wrist-motions	≤5 Hz	ABS, PLA	0.118 mW/cm^3	Wearable electronic devices, self-powered healthcare monitoring sensors
2	Bidirectional gear transmission based TENG	Motion of human foot	3.5 Hz	PLA	4 mW	LEDs, thermometer, low-power devices
3	Elastic TENG based self-powered electro-fenton system	Reciprocation by hand	2–5 Hz	Acrylic	1.95 W/m^2	Sustainable removal of methylene blue (MB) emissions, LED bulbs
4	Hybrid coaxial TENG	Rotary motion	100−400 rpm	ABS, acrylic	846.4 μW	LEDs, small toys, sensors
5	Wind-driven hybrid TENG-EMG nano-generator	Slow speed wind	6 m/s	PLA	245 mW	Subway tunnel, electronic gadgets, wireless sensor nodes, LED screen
6	Freestanding kinetic-impact-based TENG	Human motions	5 Hz	PLA	102.29 mW	Thermo-hygrometers, LEDs, smartphones, smartwatches, temperature sensors
7	Flexible TENG for vibration energy harvesting	Vibrations	6 Hz	Acrylic	608.5 mW/m^2	Portable and wearable sensors
8	3D-printed silicone-Cu fiber-based TENG	Human motion	≤5 Hz	Si elastomer	31.39 mW/m^2	Sensors, energy harvesting, LEDs, biomechanical applications
9	Integrated flywheel & spiral spring TENG	Human foot motion	≤5 Hz	PLA	38.4 mJ	LEDs, commercial thermometer, small electronic devices
10	Low-frequency resonant EMG-TENG nanogenerator	Manual vibrations	18 Hz	ABS	2.61 mW	Vibration sensors, portable and wearable electronic devices, recharging batteries
11	Novel sweep-type TENG	Rotary motion	1.2 m/s	PLA	400 V, 15 μA	Thermometer, LEDs, driver habits-monitoring, road conditions analysis
12	Mechanical frequency regulator based TENG	Human and windmill	10–50 Hz	PLA	17 V, 6.5 mA	Wireless node sensors
13	Water droplet vibrations based TENGs	Vibrations	1 to 30 Hz	ITO glass	7.55 μW	Self-powered electronic systems
14	Origami-tessellation-based TENG	Ambient excitations	3 to 16 Hz	Nylon	26.16 μW	Energy harvesting on road pavement
15	Galloping TENG based on two flexible beams	Wind energy	1.4–6 m/s	ABS, PET	200 V, 7 μA	Outdoor electric devices, LEDs
16	Direction-switchable TENG	Human joint motions	5 to 15 cm/s	PLA	5V, 10 μA	Portable self-powered electronic devices
17	Rotary cam-based TENG	Rotary motion	300−1000 rpm	PLA	3.5 mW	LEDs, commercial & industrial applications
18	Nanopillar-array architectured TENG	Wind energy	14–15 m/s	PLA	568 V, 25.6 μA	Wind energy harvesting

EMGelectromagnetic generator.
TENGtriboelectric nanogenerator.
ABSacrylonitrile poly-butadiene styrene.
PLApolylactic acid.
ITOIndium tin oxide.
[a] For references and further details of the cited papers in Table 3, please visit the supplementary file attached with this article.

4. 3DP-based manufacturing and COVID-19

During the COVID-19 pandemic, many deaths [105] have been reported throughout the world and the issues related to public health safety have become a great challenge not only on the government level but also on international platforms. World Health Organization and local administrations enforced social distancing and strict lockdown to prevent the pandemic spread [106]. Besides the massive life loss and restricted social events, the economic development of many countries was severely influenced by the shut down of industries and transportation. Due to the pandemic, the third and most substantial social, financial, and economic shock of the 21st century has been undergone.

The major problem was the shortfall of medical and basic emergency supplies during the pandemic. Since last year, many companies, especially medical industries, have been influenced by the interruptions in manufacturing and shipping, and many were imposed to delay or turn down the new contracts. After the outspread of COVID-19, the manufacturers were forced to expand the supply chains and minimize their susceptibility to deal with the concerns regarding the deficiency of medical equipment such as personal protective equipment (PPE), ventilators, face shields, respirators, gloves, hand sanitisers and gowns.

4.1. Why is 3D printing more suitable for emergencies like COVID-19?

The rapid prototyping and digital adaptability of 3-Dimensional printing enabled the quick mobilization of the technology, which can be an effective response to emergencies. Despite severe disruptions in production and supply chains, certain parts could be additively manufactured by any regionalized 3D printing service globally using open-source CAD designs. Furthermore, the additive nature of 3DP provides easy customization of complex designs. The wide range of 3DP applications against COVID-19 are personal protective equipment (PPE) [13,25], testing [107] and medical [108] devices, emergency dwellings [12], visualization aids, and personal safety gadgets.

4.2. Role of 3DP during COVID-19

3D printing technology is extensively used to develop PPE for medical staff and patients worldwide. The private sectors and individuals used their 3D printers during the COVID-19 pandemic to develop protective masks, safety goggles, ventilator parts, contact-free door handles, manikins, respirators, and charlotte valves [12,109] for healthcare professionals. During the pandemic, the companies, including Carbon, Shapeways, and Stratasys, swiftly contributed to print and provide highly-needed face masks, medical test equipment, ventilator parts, respirator valves, and custom medical components [110]. Several manufacturers have started to 3D print safety goggles and small individual quarantine booths and donated them to hospitals. A famous sports car manufacturer “Ferrari” initiated the 3DP fabrication of fittings for safety masks and respirator valves for healthcare professionals [110].

Table 4
Technological, economic, environmental and social aspects of 3D printing.

Aspects of 3DP	Description	Source
Technological	Research, documentation, preservation, cultural heritage, and educational purposes	[78]
	Home fabrication and business model innovation	[79]
	3D printed electronics	[80]
	Fabrication of functional heat exchangers and turbine blades	[81,82]
	Energy harvesting (ocean, wind, human body, vibrations etc.)	[78]
	Energy-efficient Internet-of-Things (IoT) wireless sensors	[83]
	Additive printing of jewellery and fashion products	[84]
	Surgical planning, prosthetics, organ printing, implants, tissue engineering and scaffolds	[85,86]
	Repair of complex aerospace components such as engine blades/vanes and combustion chamber	[87]
	3D printed nasopharyngeal swabs for diagnosis and emergency respiration device	[88]
Economic	3DP is expected to be a 230–550 billion US $ market by 2025, with significant economic impacts for high-value, low volume and customized products	[89]
	3DP is considered to influence five significant markets by 2025, including consumer goods, aerospace, automotive, medical equipment and tooling	[10,90]
	3DP enables complex geometries and lightweight designs, leading to reduced product life cycle costs and fuel savings in aviation	[91]
	High automation of 3DP changes labour patterns, labour workforce is needed only in pre-processing and postprocessing (suitable for developed countries)	[92,93]
	An expected decline in exports and imports	[94]
	Shorter supply chains, reduced need for tooling & centralized manufacturing, digital designs replace physical goods in supply chains	[9,95]
	Reduced time from manufacturing to market and consumption of transportation	[10,96]
Environmental	Significantly reduced manufacturing-, material-related and life cycle energy demands of products and their CO_2 emissions due to shortened and more direct manufacturing	[97]
	Reduced energy demands and CO_2 emissions of airplanes and cars due to 3DP based lightweight designs, cost-effective manufacturing of complex geometries	[90,98]
	In aerospace manufacturing, 3DP tends towards a buy-to-fly ratio of almost 1:1, leading to a significant reduction in resource demands and waste amounts	[99]
	3DP needs no lubricants, coolants, or other environmentally harmful substances	[10]
	3DP can re-use up to 95–98 % of the unfused raw material and up to 40 % saving of material-wastage	[100]
	Energy demands and CO_2 emissions due to industrial manufacturing are expected to reduce by maximally 5% through 3DP by 2025	[10]
Social	Enhanced availability of localized means of production in consumer countries	[9]
	Information technology education is required as a consequence of a rapid shift of companies towards 3DP based digital designs/ideas	[101,102]
	Socio-economic development in rural areas due to the easy accessibility of the objects	[10]
	Spare parts or lab equipment can be fabricated on-demand anywhere owing to an open-source 3DP	[103]
	Need strict control of 3DP technologies due to the availability of open-source firearms and blueprints of weapon designs	[104]
	Compatible for emergencies like COVID-19 pandemic due to design mobilization and reduced need for the human workforce	[88]

The staff and graduate students at Purdue University put their efforts into redesigning and printing the complex parts of ventilators, safety glasses, and face shields [109]. Moreover, researchers from various universities have collaborated to make a holographic microscope[2] using 3D printed parts that can be used to diagnose diabetes, malaria, sickle cell disease, and others. Automobile makers like Tesla, General Motors (GM), and Ford started to play their roles against pandemic by rapidly prototyping the ventilator and PPE parts significantly to increase the equipment supply to the victims and medical professionals [109]. Some other innovative contributions of 3DP in the fight against the pandemic are nasopharyngeal swab for preventive/diagnostic testing [111], face shields [112], test tubes, medical gloves, connectors, syringes, and ventilators valves [113], as shown in Fig. 7.

4.3. Additively manufactured face shields

3D printing was recently used to develop a lightweight and ergonomic face shield needing no accessories (clips or elastic bands) [23]. The shield was 3D printed using polylactic acid. Finite element analyses were conducted in ANSYS Workbench to verify the structural design by simulation of wearing and head holding positions. A single face shield of less than 10 g was produced in less than 45 min. The printed prototypes and procedures are shown in Fig. 8. The specification functions used to optimize the mask's design were design for additive manufacturing (DfAM), elasticity, comfort, ease of maintenance, single-frame design, lower weight, biodegradability, multi-facility manufacturability, low production time, and high productivity. Additionally, an effective design for additive manufacturing of the shield was proposed. DfAM is a method of design used to optimize the device's performance with key product lifecycle considerations, including reliability, cost, and manufacturability.

4.4. AM of emulsion inks to produce respiratory protective device

Additive manufacturing of emulsion inks, based on emulsion templating, is used to develop porous materials (porosity ranging from the submicron to 100 s of μm). 3D printing can be employed to monitor the bulk shape by governing micron porosity using emulsion ink. Usually, the emulsion templating can be combined with material extrusion or VAT photopolymerization to make a respiratory filter preventing respiratory tract and COVID-19 infections [24]. The purpose of using the polyHIPE mask is to filter harmful particles and viruses from the inhaled air. A polyHIPE material was printed with a syringe and exposed to ultraviolet light using an FDM printer. After polymerization, a porous structure was developed, as shown in Fig. 9.

The combination of emulsion templating with 3D printing, owing to its enhanced capability to develop porous structures, can be a potentially useful technique to manufacture respiratory protective equipment against viral and bacterial infections. However, some challenges need to be addressed given as follows,

(a) A specific emulsion-based AM technique is needed to be selected. Especially, an aerosol filter is a component of the RPE, used to prevent the spread of COVID-19
(b) A 3D-printed polyHIPE-based respirator needs to qualify strict requirements, including sufficient permeability to air, standardization for air flow resistance, and capability to attain high filter efficiency
(c) Scalability of the combined printing-emulsification process is required to ensure the fabrication of reproducible structures with

[2] Data obtained from (3dprintingindustry.com).

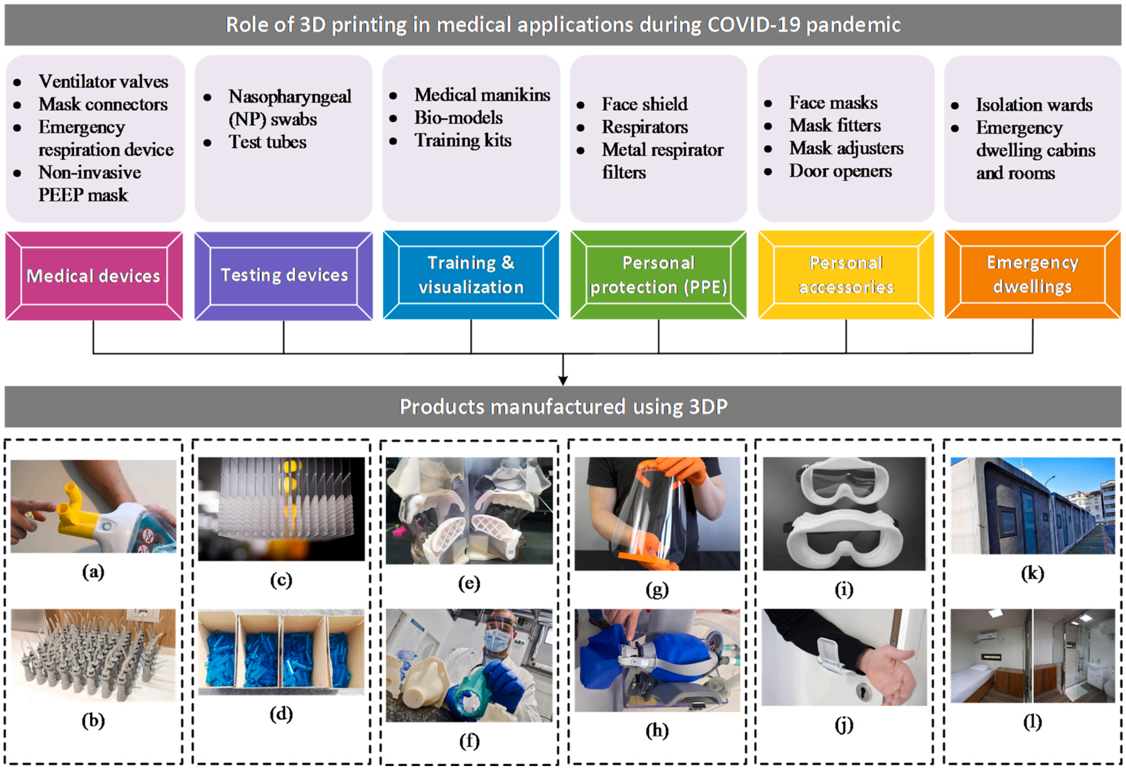

Fig. 7. Applications of 3D printing during COVID-19 outspread (a) Valves used to convert the snorkeling face masks into ventilator (b) Valves for respiratory devices (c) nasopharyngeal swabs (d) syringes (e) medical manikins for swabs (f) Silicon masks (g) protective face shields (h) emergency respiratory equipment (i) safety goggles (j) contact-free door handles (k) isolation wards (l) isolation houses equipped with a bed, shower, and toilet.

high control over porosity along with interconnectivity between batches

(d) Emulsion stability is a critical parameter to be controlled if the printed respiratory filters are to be stored for an extended period
(e) Materials extrusion is more recommended to be used in conjunction with emulsification for printing respiratory filters due to its capability to maintain an open outer porosity
(f) 3D printing of emulsion inks is a time-consuming process
(g) Only recommended for customizable and complex applications that the conventional manufacturing cannot develop
(h) Emulsion based AM is not recommended for aerosol-based filter applications that strictly involve the utilization of porous membrane
(i) Specific mold materials should be selected to inhibit the development of a surface skin on the polyHIPE surface from allowing proper air permeability

4.5. *Additively manufactured biodegradable face masks*

3D printing and electrospinning can be used in combination to produce biodegradable, recyclable, and transparent mask filters from polylactic acid [25] for medical healthcare applications. A hierarchically structured nanoporous filter was developed by printing the PLA struts on a nanofiber-based web. The nanofibers were fabricated through electrospinning and deposited on an Al foil. The pellets of polylactic acid were extruded through a twin-screw extrution setup to develop the filaments. An FDM printer was used to print the nanofibers with a 0.4 mm diameter nozzle. The process is shown in Fig. 10. The aluminum foil was shielded with the nanofiber and pasted on the printing bed. The PLA layer integrated with nanofiber was separated from the Al foil to achieve a flexible mask filter. The PLA-based mask filter exhibited admirable filtration efficiency. The 3D printed PLA substrate gives additional strength and support to the nanofibers. The translucent mask can also be used in lip-reading for people with hearing impairment. The PLA-based masks are recyclable and biodegradable. Moreover, the multi-layered 3D printed filter revealed KN95/N95-equivalent filtration performance.

4.6. *Development of ideal tissue platform through 3D bioprinting for COVID-19 infection*

3D bioprinting is personalized medicine that can be well-defined as the automated manufacturing of biologically functional devices from bioactive molecules, living cells, cell aggregates, and biomaterials through a combination of tissue maturation and 3D printing [114]. It is widely used to develop complex 3D functional living tissues and artificial organs with basic building blocks, including living cells, biological components, drug particles, proteins, and nucleic acids, with accuracy. The applications of 3D bioprinting are toxicology, drug discovery, fabrication of tissue models for research, and artificial functional tissues/organs for transplantation. Bioprinted systems can be used for a better understanding of the mechanisms causing diseases and physiological phenomena involved in the detection, treatment, and prevention of the ailments. The basic building blocks used in bioprinting are bio inks, generally made of various types of cells, biomaterials, or proteins. Bio inks can be categorized by printability, biocompatibility, and bioactivity [115] and can be classified as [116]:

a) Hybrids of natural substances such as alginate, hyaluronan, agarose, silk fibroin, chitosan, cellulose, gelatin or fibrin, and collagen
b) Mixtures of synthetic/natural components
c) Synthetic biomaterials
d) Combinations of particles and hydrogels
e) Bio inks for 4D printing
f) Combinations of various cells and soluble factors

Hydrogels are biocompatible in nature and characterized by

Fig. 8. 3D printed ergonomic, light weight and Single frame designed medical face shield using FDM Copyright: © 2020 Celik, et al. [23].

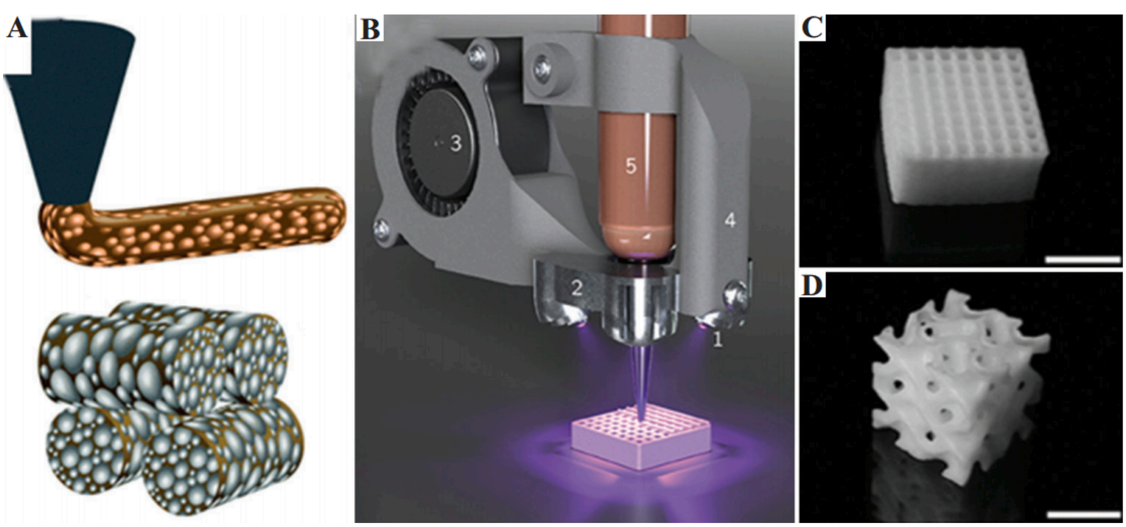

Fig. 9. (A) A 3D printed silica-chitosan-based emulsion (B) Cure of an extruded emulsion under UV light immediately after 3D printing of a photo curable emulsion, (C and D) 3D printed polymerized high internal phase emulsions based structures Copyright: © 2021 Sherborne and Claeyssens [24].

physicochemical attributes comparable to biological tissues. They are extensively used for drug delivery [114] and have found various applications in phototherapies for the treatment of numerous diseases [117].

Similarly, in a previous study [118], viscoelastic silicone, also known as SIL30, was 3D printed by the ultra-violet (UV)-curable Digital Light Synthesis (DLS) process. DLS is an emerging 3D printing technology that facilitates the accelerated 3D printing of soft polymers. The additively manufactured SIL 30 was experimentally investigated to study the thermo-viscoelastic characterization of the soft polymer at various temperatures ranging from −20 °C to 60 °C and variable strain rates under tensile loading. 3D printed SIL 30 exhibited a strong strain rate-dependent behaviour and a strong capability to design intricate and complex metamaterials for biomedical applications. The printed silicone

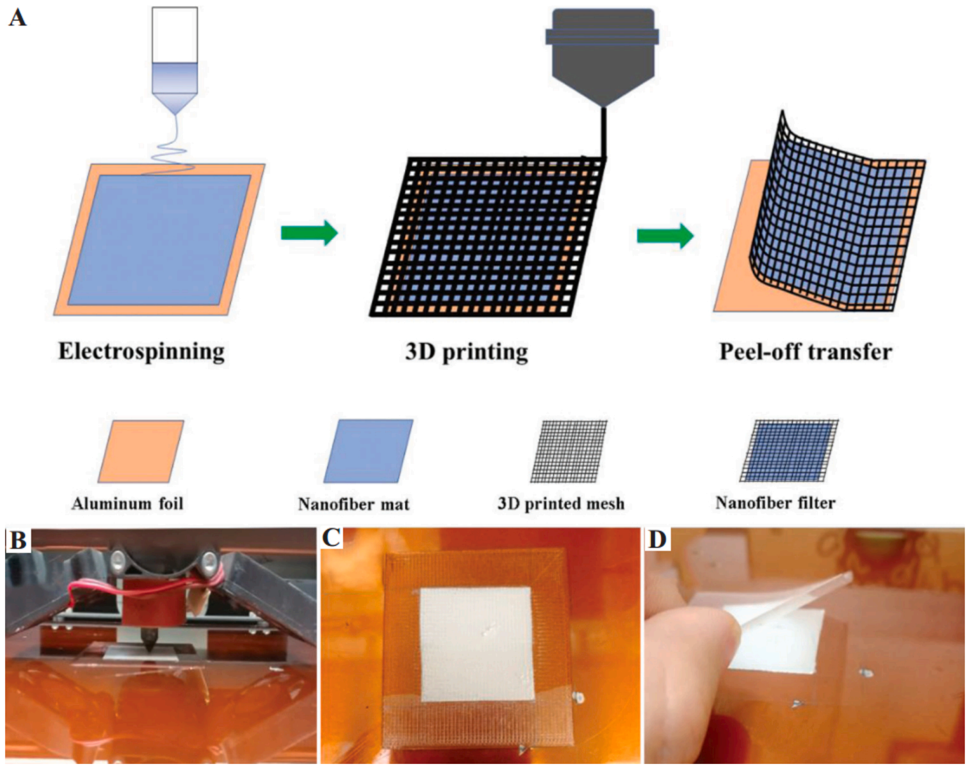

Fig. 10. (A) Fabrication of biodegradable mask filter using 3DP and electrospinning, and the constituent materials (B) printing process; (C) printed object; (D) peel-off (the sample is reflected on the base plate) Copyright: © 2020 He, et al. [25].

ruptured at strains above 200 %, showing significantly large stretchability, and can be used to design and simulate more complex cellular metamaterials. In addition, the SIL30 possesses excellent biocompatibility and high tear-resistance. Therefore it can be an effective candidate for human skin-contact applications such as wristbands, headphones, and other wearable electronic devices.

The 3D bioprinting, along with microfluidics and organoid formation, is significantly used to develop in vitro tissue models in antiviral research [26]. Currently, a COVID-19 test tissue model was developed by integrating the 3D bioprinted kidney, lungs, blood vessels, heart, intestine, and nasal mucosa (olfactory organs). The individual artificial organs were made from various cells and hydrogels [26], as shown in Fig. 11. The bioprinted organs were joined together through microfluidic channels facilitating oxygen and nutrients supply to cells, cell migration, and virus transmission. Bio ink was developed using hydrogels and cells to achieve realistic morphology/functionality. The challenge in developing the model was developing the immune response against COVID infection. The potential challenges confronted by 3D bioprinting are the lower printing speeds and resolution. Furthermore, the diversity of materials needs to be enhanced to efficiently mimic biological tissues and organs' structural, mechanical biological, and optical characteristics.

4.7. New IT-driven rapid manufacturing

The emergency supplies to be fulfilled in public emergencies such as COVID-19 pandemic mainly consist of the following two types [27] (1) Basic supplies: necessary for livelihoods such as food, fuel, shelter, and clothing (2) Medical supplies: needed to protect life, including first-aid medication, masks, sanitizer, ventilators, personal protective equipment (PPE), and temporary dwellings. In normal circumstances, the production and supply of these necessities depend on market trends. A modified mechanism should be followed in emergencies to meet the peak demands for both medical and basic supplies. New information technology (IT, also known as intelligent technology) based on rapid manufacturing [129] is an effective technology to meet emergency requirements. The comparison between the two different approaches: traditional IT and new IT, along with the merits of new IT, are highlighted in Fig. 12(a). Traditional IT employs computing, network, storage, system software, infrastructure, and operating system (OS), to attain desired business efficiencies. However, new IT is based on the Internet of Things (IoT), cloud computing, 5 G applications, big data, artificial intelligence (AI), and the digital twin. New IT, owing to its capability of decision-making and an improved acquisition, transmission, and analysis of data, provides more reliable systems, faster launch time of services, and intelligent maintenance of systems to cope with the crisis encountered by the COVID-19 pandemic. The working strategies of new IT [27] are enlisted below,

(a) The design is accomplished through a new IT-driven procedure
(b) The behavioral survey of the user and environmental factors are processed through the IoT
(c) Designers can convert the customer demands into high-quality products and features through artificial intelligence and big data
(d) The design scheme can be virtually verified via digital twin to identify the design faults and improve them rapidly

Consequently, new IT facilitates an efficient and flexible design and development of emergency supplies with shortened cycle and reduced costs. Furthermore, raw ingredients, intermediate parts, and final products can be delivered to the user as quickly as possible without interruption to achieve rapid supplies in emergencies. The policies required to implement the new IT-driven strategies to quickly meet the emergency medical and basic supplies during the COVID-19 pandemic are given in Fig. 12(b).

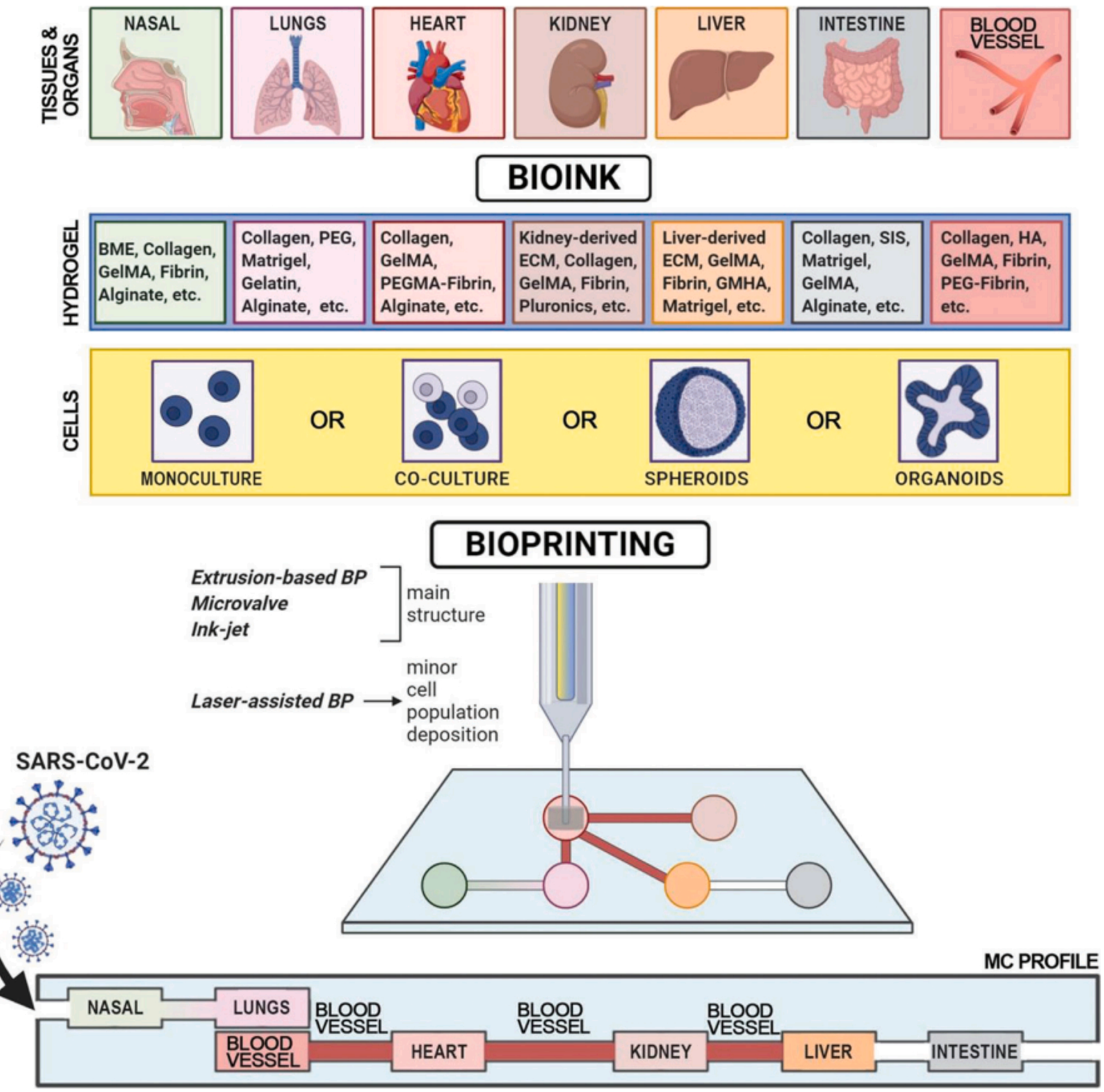

Fig. 11. Design of an ideal tissue platform to study COVID-19 infection. BP – bioprinting; BME – basement memebrane extract; BV – blood vessel; GelMA – gelatin methacrylated; ECM – extracellular matrix; GMHA – glycidyl methacrylated hyaluronic acid; PEG – polyethylene glycol; MC – microfluidic chamber (chip); PEGMA – polyethylene glycol monoacrylate; SIS – small intestinal submucosa; SARS-CoV-2 – severe acute respiratory syndrome-related coronavirus 2, Copyright: © 2020 Shpichka, et al. [26].

4.8. Other potential applications against COVID-19 pandemic

The most significant 3D printed medical devices combating the shortfall of emergency supplies during COVID-19 pandemic, including stopgap face masks, nasopharyngeal swabs [16], respirator mask [15], quarantine booths [16], face shield, (f) T-connectors/Y-connectors for ventilators, ventilator valve [20], air-purification respiratory hood, 3D printed pills, artificial lung used for lung disease treatment, 3D-printed capsules [14], venturi valves, door handles, and Creality goggle design [30] are shown in Fig. 13. In addition, some other advances in the applications against COVID-19 in various technologies such as, robotics, Artificial Intelligence (AI), telemedicine, Big Data, mathematical modeling, Internet of Things (IoT), and nanomedicine are summarized in Table 5.

4.9. Influence of COVID-19 pandemic on manufacturing industry

The global COVID-19 crisis inevitably has had a significant impact on the manufacturing industries. Due to a considerably wide range of impact and an extensive duration of the pandemic, the manufacturing industries faced many challenges, including service delays and difficulty in continuing business and material allocation. The pandemic has influenced the manufacturing industry in the following aspects,

Material supply – manufacturing companies had to face challenges related to supply chain disruption, availability of raw materials and inventories due to social limitations posed by the pandemic

Logistics and transportation – the logistics of air, railway, and road transportation are facing a delay in goods delivery due to control and prevention measures taken for the pandemic

Manufacturing side – personnel activities and movement of people were restricted due to regular disinfection and other pandemic preventive measures. The labor efficiency and productivity reduced due to the implications of healthcare-related enforcements

Market side – overall market demand was declined to lead to survival challenges for companies

All over the world, governments and non-traditional companies made efforts to fulfill the supplies of facemasks and ventilators by ramping up the production of required healthcare equipment. However, there is still a lack of medical health care equipment that has to come from somewhere. In this regard, 3D printing companies and educational institutions have been able to fill the void with industrial or personal 3D printers by manufacturing the needed parts. Some well-recognized 3D

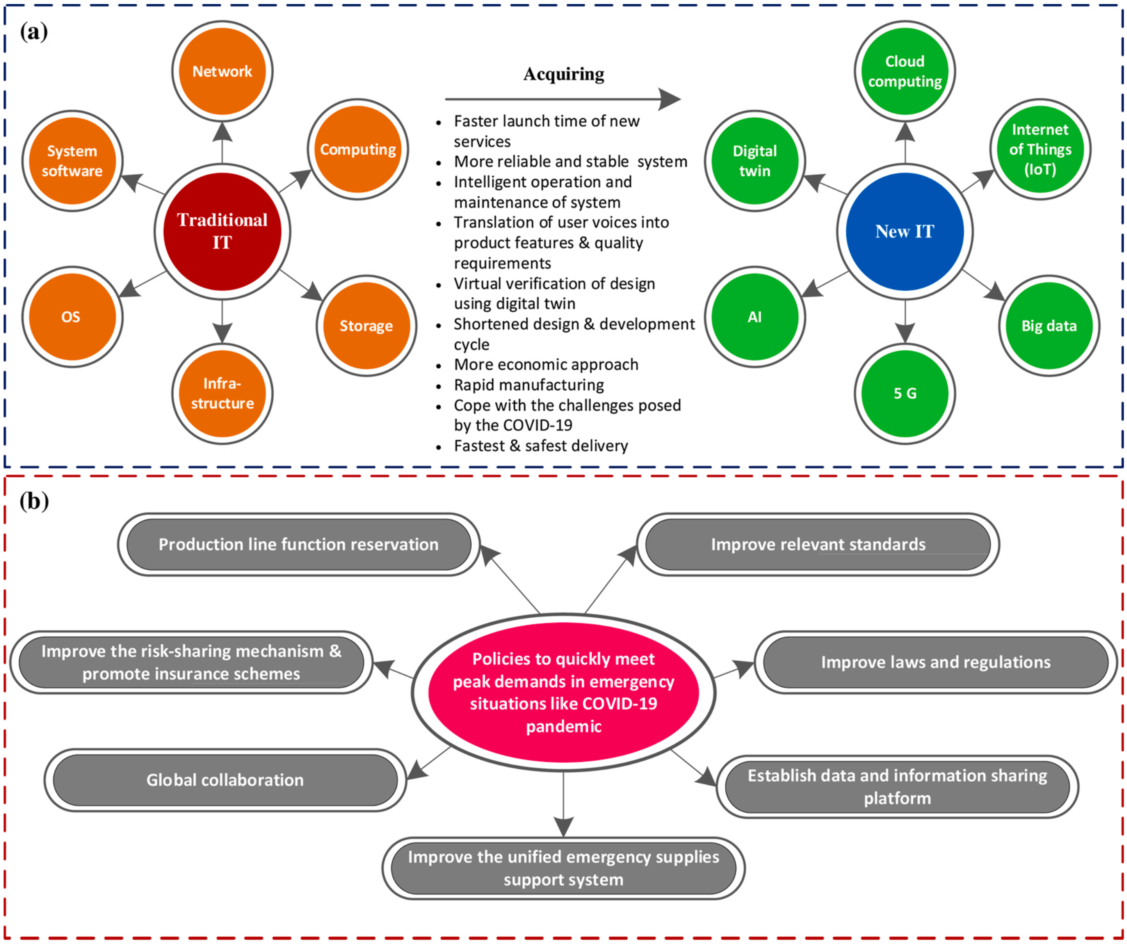

Fig. 12. (a) New IT-enabled rapid manufacturing and (b) policies to quickly meet basic and medical emergency demands in the COVID-19 pandemic crisis.

printing companies, including Stratasys Ltd., 3D Systems Corp., Proto Labs Inc., and HP Inc, contributed by making the necessary medical equipment and sending parts to local hospitals. In addition, a well-known company named Tinkerine Studios, renowned for designing and manufacturing 3D printers and related software and educational content, quickly pivoted to produce required medical equipment when it noticed the market demand. Interestingly, the market share price and investor interest surged by 70 % during Feb-Apr 2020, exhibiting an increased demand for the 3D printing market,[3] as shown in Fig. 14.

5. Intellectual background of 3D printing

The schematic shown in Fig. 15 reveals the step-by-step procedure followed to perform the bibliometric study of 3DP-related research.

5.1. Data retrieval and research methodology

From the Web of Science Core Collection (WOSCC), the databases used to obtain the 3DP-related published data were Science Citation Index Expanded and the Emerging Science Citation Index from the library of Northwestern Polytechnical University, China. The peer-reviewed and original articles published in English between 1986 and 2021 were collected, and the conference proceedings, review articles, and books were removed. Finally, 1589 articles were nominated for bibliometric investigation and saved in plain text format, including a list of references and a complete record.

5.2. Bibliometric investigation in CiteSpace

CiteSpace, an open-access Java-based software, was used for the bibliometric study of 3D printing. A project was created with 1589 studies, and the following settings were established in CiteSpace, as shown in Table 6.

During simulations, two metrics, including (1) betweenness centrality and (2) burst strength, were employed to determine the critical nodes in the visualization map. Each entity is reflected a node in the visualization map, separated by linking specified thickness and length paths. Thus, the betweenness centrality of the specialties can be evaluated by the ratio of the smallest path between the two nodes and the sum of all the smallest paths, as given by Eq. (1) [127].

$$Centrality(node_n) = \sum_{i \neq j \neq k} \frac{M_{jk}(i)}{M_{jk}} \quad (1)$$

In Eq. (1),M_{jk} is the number of shortest paths between node j and node k; $M_{jk}(i)$ is the number of paths passing through the node *i*. The burst strength analyses were used to determine the latest hotspots in the 3DP research. In addition, knowledge clustering was conducted to determine the critical research themes.

Three bibliometric analyses were run to achieve the following goals.

1 Co-occurrence analysis: This analysis was employed to highlight the most frequently utilized keywords

[3] Based on the data obtained from (Stockhouse.com)

[4] For references and further details of the cited papers in Figure 6, please visit the supplementary file attached with this article.

Fig. 13. 3D printed medical devices for applications during pandemic (a) stopgap face mask, (b) swab [16], (c) 3D printed respirator mask [15], (d) quarantine booths [16], (e) face shield, (f) T-connectors, Y-connectors for ventilators, (g) ventilator valve [20], (h) air-purification respiratory hood, (i) 3D printed pills, (j) artificial lung used for lung disease treatment, (k) 3D-printed capsules [14], (l) venturi valve, (m) door handles, (n) Creality goggle design [30].

2 Knowledge clusters: This section categorizes the keywords and references into different clusters. The clustered information was used to design a novel knowledge structure of 3DP literature for categorizing the 3DP research into ten distinct research themes. In addition, the emerging challenges in 3DP research were highlighted.
3 Burst strength: used to highlight the research frontiers and hotspots of the 3DP research.

5.3. Analysis of co-occurring keywords

Keywords highlight the subject categories that can be used to classify the research articles. Overall, hotspots and research frontiers can be identified by investigating the co-occurring keywords and their burst strengths, respectively. Burst keywords are the keywords which were cited a lot over a period of time. From the keyword co-occurrence analysis in CiteSpace, the most influential keywords of 3DP literature are shown in the form of visualization network in Fig. 16. The keywords are represented by the nodes, where the node size gives information about their co-occurrence frequency. The top twenty keywords in 3D printing are enlisted in Table 7, based on the number of counts and centrality. The keywords with the highest frequency of co-occurrence (and their counts) are 3D printing (765), additive manufacturing (765), fabrication (201), design (174) and mechanical property (172). The most frequently searched keywords ranked on the basis of betweenness centrality (and their frequency) are biomaterial (39), reconstruction (22), fused filament fabrication (27), alloy (27), tissue engineering (26), and evolution (22).

5.4. Knowledge clusters of 3DP knowledge

The research articles published in a journal describe the frontiers of the subjects related to that journal. In CiteSpace, the clustering of the 3DP-based literature was performed using keywords to develop the knowledge structure of 3DP research. The 3DP knowledge clusters based on the retrieved research articles are represented in Fig. 17. The knowledge clusters with size, cluster-ID, labels, and silhouette are provided in Table 8. The silhouette coefficient is used to estimate how well the individuals are grouped within the clusters. The silhouette coefficient (S) can be defined by Eq. (2) [128] as given below.

$$S(n) = \frac{p(n) - q(n)}{\max\{p(n), q(n)\}} \quad (2)$$

Table 5
Role of different technologies and their potential applications in the battle against COVID-19 to fulfill emergency supplies.

Sr. No.	Technology/ Designer	Applications	Materials/ Resources/methods	Features	Ref.
1	Filament-based 3D-printing (Material extrusion)	Nasopharyngeal (NP) swabs	Polyethylene terephthalate glycol (PETG) filament	(+) Printers & plastics are readily available and inexpensive (printers <800 USD, plastics <30 USD per kg) (+) PETG is a durable & chemically inert	[119]
2	Copper3D NanoHack, 3D printing	Respiratory face masks	Polylactic Acid (PLA) filament	(+) No deterioration of plastic (+) Open-source (-) Non-adjustable (-) Manually assembled	[30, 120]
3	Prusa, 3D printing	Protective face shields	Transparent plastics	(+) Insertion of flexible shields	[32]
4	Kvatthro-Thingiverse, 3D printing	HEPA mask	Polylactic Acid (PLA) filament	(+) Effective air seal (+) Exchangeable for males & females	[33]
5	Materialise, 3D printing	Door handles	Wide range of plastics	(+) No direct skin-to-surface (+) Ready to print and accessible	[121]
6	Milan's Issinova, Selective laser sintering	Valves for oxygen masks,	–	(+) Excellent quality (+) Good performance	[29]
7	School of Pharmacy Queen's University, FDM printer	Face shields,	Acetate sheet, elastic band, and foam	(+) Open-source availability (+) Close on the forehead (+) Safe air ventilation (+) Comfortable	[29]
8	Artificial Intelligence (Machine learning & deep learning)	Study, diagnose, treat COVID-19, predict the outcome, estimate the mortality risk	CT scans & X-rays	(+) Increases knowledge of COVID (+) Rapid identification (+) Detection accuracy & reliability (+) Tracking of disease progression	[36]
9	Nanomedicine (Chloroquine)	Drug repurposing	Synthetic nano-particles (NP) with immune-modulating and antioxidant molecules	(+) Inhibit virus from entering cells (+) Prevent virus activation (+) Inflammation control (+) Prevent infection of Vero cells	[36]
10	Vaccine technology using proteins, nucleic acids, and recombinant viral vectors	Persuades a neutralizing immune response against COVID infection	Naked viral DNA, mRNA, SARS-CoV-2 S protein genes	(+) Enables the development of COVID-19 vaccine within a few months	[36, 122]
11	Mathematical Modeling (equations used to mimic reality that can be refined to discover knowledge of the virus)	Predict COVID-19 transmission rate, public policy decision-making process	Stochastic individual based model, Susceptible-exposed-infected-recovered models, and Susceptible-infected-recovered models	(+) Prevent further spread of the infectious disease (+) explains the spread of virus in a better way	[36]
12	Big Data	Prevent COVID-19, disease tracing & screening	Uses past 14-day travel history & NHIA identification card data for screening	(+) Rapid real-time evaluations	[36]
13	Internet of Things	Trace pandemic origins and ensures effective quarantine	Sensors incorporated in robots, mobile phones, and drones	(+) Online health consultations (+) Better allocation of supplies	[36]
14	Telemedicine	Provides medical care for patients at home, annual follow-ups and mental health services	Online healthcare services, remote training platforms	(+) Provides symptoms & prevention info to all patients (+) Decreases number of hospital visits	[36]
15	Robotics	Surgery, disinfection, navigation, swab testing, distribute medical supplies	Unmanned aerial vehicles, drones	(+) Reduced patient hospital stay (+) Increased hospital capacity (+) Reduced exposure to infection	[123, 124]
16	Duke university medical center, Formlabs printers	Personal protective equipment	AAMI class 3 & 4materials	(+) Significantly high protection against pathogens	[125]
17	Formlabs 3D printing	Auxetic nasopharyngeal swabs for detection and sample collection	Meta-biomaterials, photopolymer FLSGAM01	(+) Reduce patient pain and discomfort	[35]
18	Isinnova, 3D printing	Bio-cellular face shields, respirator valve prototype	Bio-macromolecules polymerized polyvinyl chloride	(+) Biocompatible material (+) Comfortability (+) Efficient production	[34]
19	Fused filament fabrication	Face shields and face masks	FDM compatible filaments	(+) Fulfill supply chain shortages (+) Tracking and evaluation of product category	[126]
20	Polyjet J735 and J750 printers, Stratasys	Fixed hand-free door openers, door hooks and button pushers	Acrylonitrile Butadiene Styrene (ABS), VeroWhite, VeroBlue resins	(+) Retractable sheath (+) Large array of devices with different geometries	[31]

where n shows the number of elements in the dataset, $q(n)$ is the average dissimilarity of elements n linked with other elements within the cluster, and $p(n)$ indicates the minimum average dissimilarity of the element n with all other elements within the neighboring clusters. A smaller value of $q(n)$ means n is a better match within its cluster, whereas a significantly higher value of $p(n)$ means n is not a good match with its neighboring clusters. The silhouette coefficient of a cluster lies between 1 and −1. The terms with silhouette closer to 1 represent a high degree of consistency of the articles. The silhouette greater than 0.5 shows good clustering of the data. During simulations, all the clusters exhibited a silhouette greater than 0.75, justifying accurate clustering of the data. The largest cluster (#0) was Composite materials with 30 articles and a silhouette of 0.881, whereas the cluster with the latest and most essential subtopics was (#6) electrochemical microprinting, with 22 articles and a silhouette of 0.947 (reported in 2019).

5.5. *Knowledge structure*

The keywords-based knowledge cluster was used to develop a state-of-the-art knowledge structure of 3D printing showing the hierarchical

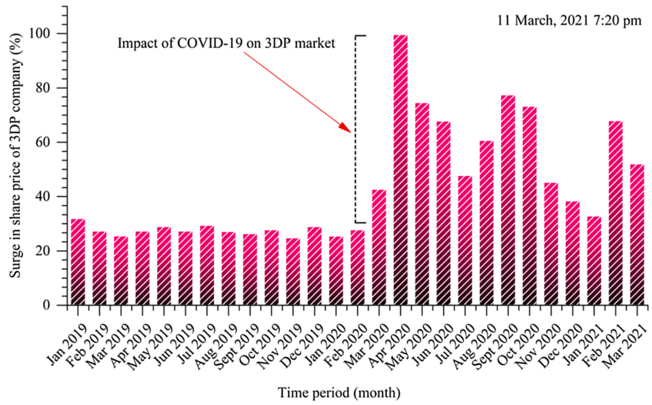

Fig. 14. Effect of COVID-19 pandemic on the market share prices of 3D printing company Tinkerine Studios Ltd. Canada in response to an increase in 3DP market needs.

relationship among 3D printing subtopics, keywords, and clusters. The 3DP knowledge was categorized into ten research themes based on knowledge structure (subtopics), co-occurring keywords (knowledge base), and relevant clusters (knowledge domain), as shown in Fig. 18, including energy efficiency/ sustainability, defects/inaccuracy in 3DP, matrix composites/reinforcement, control parameters, resources management, mechanical/thermal properties, materials used for 3DP, applications/classifications of 3DP, biomimicry, and simulation/testing.

Simulation/testing was the most significant subtopic in 3DP research, including mathematical modeling, design optimization, simulation, experimental testing, and fabrication of the 3D printed objects. The second most important domain, biomimicry/nature inspiration, includes replicating the concepts and designs provided by nature to design economic structures or new materials for novel technological innovations. For example, biomimetism is widely used in 3D printed prosthetic implants [130], tissue engineering [42], and dental implants [47].

The next is the applications/classifications of 3DP, such as electrochemical microprinting, direct ink writing, and fused filament fabrication, widely being used in bone tissue engineering [40], flexible electronics [41], aerospace components [37], drug delivery [39], water purification [43], and soft robotics [38].

The materials used in 3D printing are ceramics, metals, polymers, concrete, and Portland cement [37,44]. The significance of the mechanical/thermal properties of 3D printed objects is studied in various studies. The knowledge of fatigue and thermal characteristics is critical in the aerospace/automotive industries. Some commonly investigated attributes of printed components are surface roughness, tensile properties, stiffness [131], thermal conductivity, yield stress [132], fracture toughness [133], and micro-hardness [134]. The capability of 3DP to make customized parts and digitalization of the product design improves supply chain management regarding reduced transportation costs, minimal inventory, and lower capital costs of warehouses/factories [135]. 3D printing has played an important role in adopting socially sustainable supply chain strategies.

The matrix composites and reinforcement can be developed by two methods: (i) combining two similar materials, for example, alloys, and (ii) hybridizing two different materials to develop a reinforced composite, for instance, carbon fibre reinforced polymers. The most valuable composites are polylactic acid (PLA)-carbon fiber composites [136] and carbon nanotubes-Ti-6Al-4 V composites [137]. Aerospace components and medical implants are required to be manufactured with high-precision, minimized errors, and fewer defects in 3D printing.

Table 6
The settings for the control parameters in CiteSpace for bibliometric study of 3DP research.

Sr.	Settings	Selections
1	Time slicing	Years span from 1986 to 2021; slicing with one year
2	Term source	All (including title, authors, keywords, and abstract)
3	Node type	Keywords, cited journals, Authors, country, institutions, cited authors, and cited references
4	Criteria of selection	Top 20 %
5	Pruning settings	Pruning sliced networks and Pathfinder
6	Links	Default
7	Visualization	Merged networks and Cluster view-static

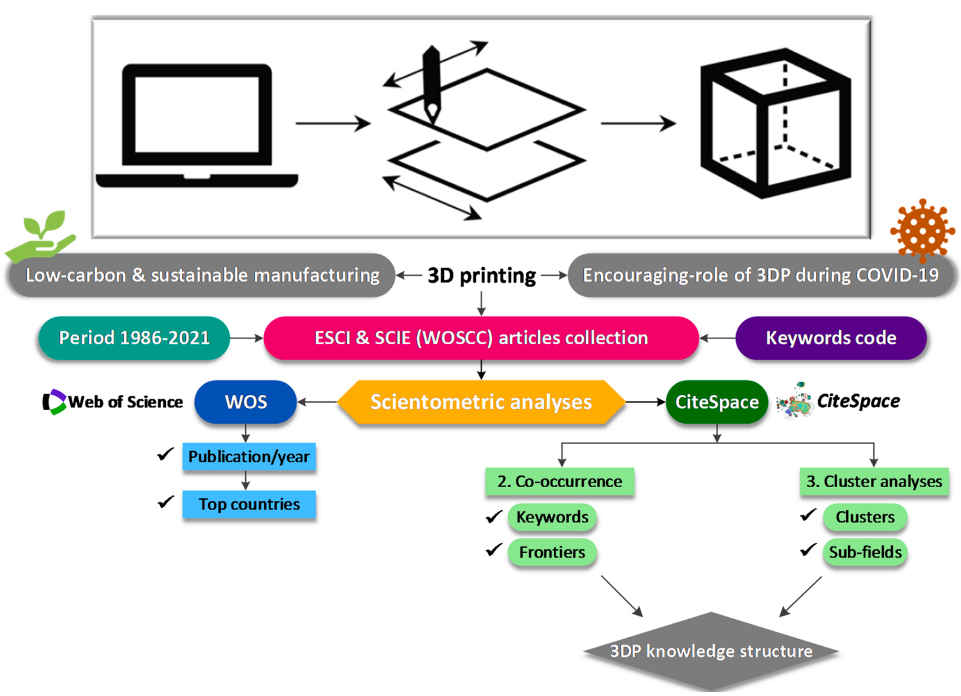

Fig. 15. The accomplished procedures for the current study.

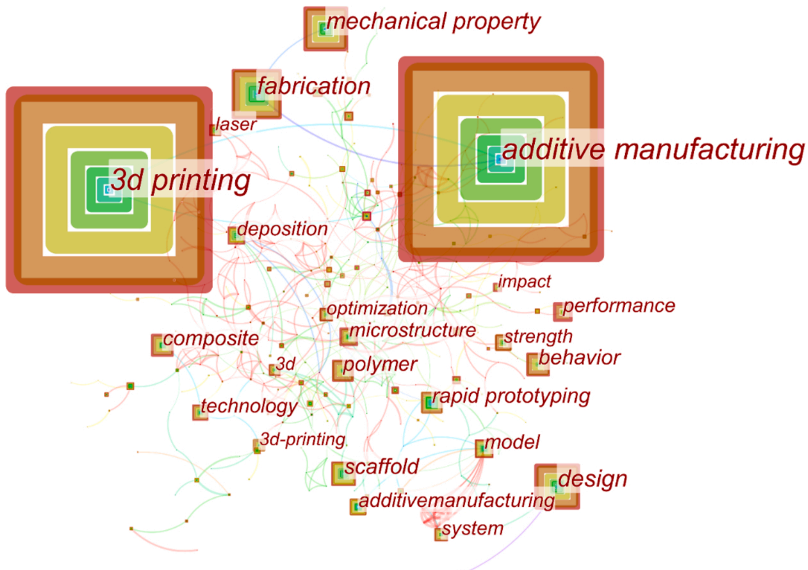

Fig. 16. The keyword co-occurrence map of 3DP-related research.

Table 7
Top 20 most influential keywords in 3DP ranked by centrality and usage frequency.

Frequency-based classification				Centrality based classification		
Ranking	Counts	Year	Keywords	Centrality	Year	Keywords
1	765	2012	3D printing	0.18	2013	biomaterial
2	765	2011	additive manufacturing	0.18	2016	reconstruction
3	201	2012	fabrication	0.17	2017	fused filament fabrication
4	174	2011	design	0.16	2016	alloy
5	172	2013	mechanical property	0.15	2013	tissue engineering
6	100	2015	scaffold	0.15	2016	evolution
7	95	2014	behavior	0.13	2014	model
8	92	2014	composite	0.12	2013	optimization
9	91	2008	rapid prototyping	0.11	2016	extrusion
10	89	2014	polymer	0.1	2015	3D printing
11	78	2014	model	0.09	2014	nanoparticle
12	71	2015	microstructure	0.08	2016	temperature
13	71	2017	performance	0.07	2014	polymer
14	70	2013	deposition	0.07	2015	construction
15	68	2014	Additive manufacturing	0.07	2015	fiber
16	67	2014	technology	0.07	2015	powder
17	61	2014	System	0.06	2008	rapid prototyping
18	59	2016	strength	0.06	2015	microstructure
19	58	2013	optimization	0.06	2016	rheology
20	52	2015	laser	0.05	2013	hydrogel

Therefore, various efforts have been conducted to solve the problems related to wear, error propagation, corrosion, damage assessment [138], and quality control in the 3DP process. Renewable energy harvesting using 3D printed mechanical energy devices is the most sustainable aspect of 3D printing, which involves harnessing small fractions of valuable energy from various ambient sources. As mentioned above, 3D printed nanodevices are widely used to harvest solar, wind, and mechanical energy.

5.6. Research frontiers and hotspots of AM

Citation bursts of the most significant keywords or documents provide information about the hotspots and research frontiers of the research field over a specific time period. The frequency of citation of the keywords or documents can be plotted against time to distinguish the significance of the hotspots. These hotspots are the research areas/topics needing more significant research efforts for further advancements of the field in the future. Currently, the hotspots were evaluated from the keywords with strongest citation bursts. In Table 9, the most important 11 keywords, their burst strengths, and corresponding timeline trends are enlisted.

The hotspots can be significantly effective for the researchers for further development and determination of potential challenges in that area of research. The hotspots or research frontiers of 3DP-related research, with their brief introduction and recent trends, are presented in Table 9 in descending order of their burst strengths. The 3DP hotspots include energy, sustainability, strength, stability, tensile properties, 3DP device, direct ink writing, carbon nanotube, rheology, polymer composite, and fused deposition modelling.

6. Potential challenges incurred by AM

Techno-socio-economic analysis, the applications in renewable energy generation systems and the extensive role of 3D printing in the battle against the COVID-19 pandemic reveal the sustainable aspects of additive manufacturing in the development of a sustainable energy environment. Still, the replacement of conventional manufacturing by 3D printing is a great challenge to achieve high productivity, mass

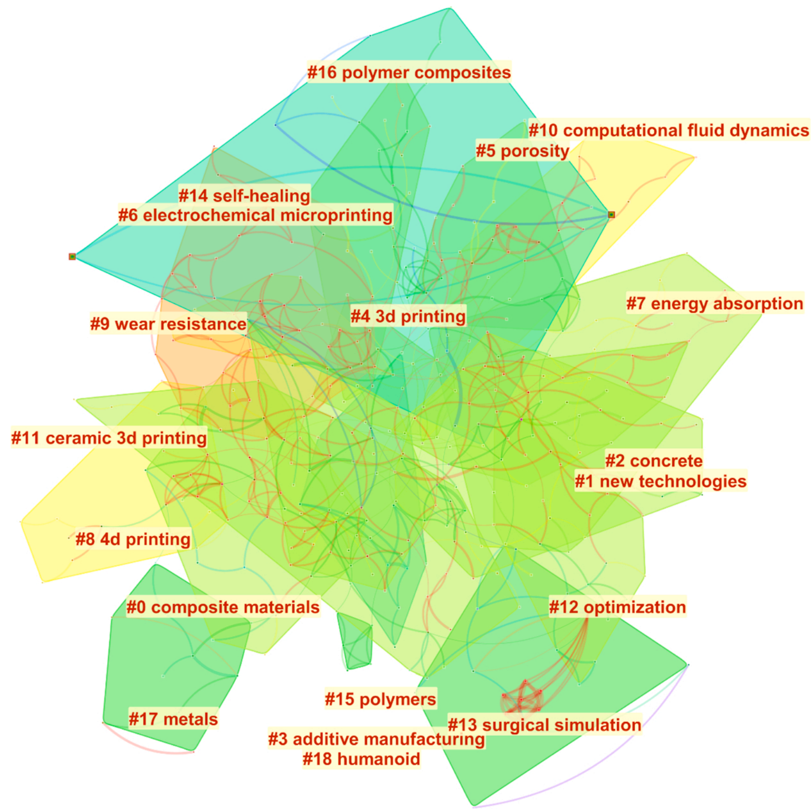

Fig. 17. Clustering the 3DP knowledge using the co-occurring keywords.

production, high mechanical and thermal properties for wide ranging applications. Henceforth, to study the prevailing challenges and their possible solutions, as enlisted below, are highly recommended for future research for further enhancement of additive manufacturing technologies.

Low printing speeds – selection of suitable printing methods is critical for manufacturing parts for aerospace, automotive, and biomedical applications.

Low mechanical strength – components undergoing high mechanical deformations, extreme stresses, fatigue, torsion, and vibrations such as shafts, bearings, couplings, pistons, and gears are produced by conventional manufacturing methods. 3D printing can repair the components, but the fabrication of crucial industrial parts is still a big challenge.

Stability and surface finish – various materials used in biomedical applications, tissue engineering, and transplant organs should be stable enough to withstand varying chemical reactions. Moreover, the components such as artificial organs, stunts, dental and surgical instruments require a high surface finish.

Thermal stability – fabrication of certain mechanical components using AM, including piston rings, turbine blades, radiator tubes, and heat exchangers. that are used under severe environmental circumstances such as high temperatures and high pressures, is a potential challenge that needs to be addressed.

Mass production – Bulk manufacturing or batch production using AM is not feasible and traditional methods can not be fully replaced with 3DP based manufacturing

Sustainable energy applications – Applications of 3D printing to fabricate substrates, encasings, and structural members for nano-scale energy harvesting mechanisms are reported. However, the utilization of AM for large-scale sustainable energy generation systems with output power in Watts or kWatts is rarely demonstrated.

The potential challenges that the AM industry had to face during the outspread of the COVID pandemic can be categorized concerning design, safety, manufacturing, certification, and legal issues [20], as shown in Fig. 19. The design challenges may occur during initial stages of manufacturing. The additively manufactured components to be used in direct contact with human organs or tissues such as skin, or face need to fulfill safety precautions. For instance, ventilator valves, filter masks, and nasal swabs are very sensitive devices that should fulfill the criteria of human comfort, and appropriate functionality. Hence, various safety precautions have to be considered while designing all 3D printed items.

A potential challenge is the development of advanced printing materials for biomedical applications. Another issue is the limited knowledge of suitable raw materials for the assortment of optimal printing processes also becomes crucial due to the restrictions in design, health, and safety regulations. It was challenging for the manufacturers and designers to finalize the processes and materials for the mass production of emergency supplies. Moreover, the materials for the medical instruments used directly in human contact need to be selected with extra caution. Manufacturing of complicated geometries for medical devices that require fulfilling standardized specifications, dimensions, and performance, are challenging to be reproduced through 3D printing. Another key challenge is related to the copyright and Intellectual property infringement lawsuit issues in the bulk production of additively manufactured items.

The disparity among developed, developing, and underdeveloped countries due to unfamiliarity and unequal distribiution of expensive 3D printing technology is also a potential barrier. The challenge of certification required to meet the regulations and eliminate liability risks for public printing of PPE or medical accessories for the pandemic cannot be underestimated. Finally, the optimization of the product design to meet the customer feedback and considerations for mass production, should be considered.

Table 8
Significant knowledge clusters (based on keywords co-occurrence) of three-dimensional printing research.

Cluster-ID	Size	Silhouette	Mean (year)	Label (*LLR)
0	30	0.881	2017	composite materials; lattices; microwave devices
1	27	0.973	2017	new technologies; energy consumption; supply chain management
2	26	0.93	2017	concrete; osseointegration; performance
3	26	0.825	2017	additive manufacturing (AM); quality control; design of AM (DfAM)
4	26	0.976	2015	3D printing; additive manufacturing; hydrogels
5	23	0.954	2017	porosity; orthopaedic implants; hip arthroplasty
6	22	0.947	2019	electrochemical microprinting; fluidfm; functionally graded materials
7	22	0.934	2017	energy absorption; stiffness; behavior
8	22	0.96	2017	4D printing; energy harvesting; soft robotics
9	21	0.928	2018	wear resistance; robocasting; texture; wear;
10	20	0.917	2018	computational fluid dynamics; cualmnni; graphene foam
11	18	0.954	2018	ceramic 3D printing; bone; direct ink writing
12	18	0.813	2017	optimization; layered manufacturing; 3D printing
13	17	0.989	2016	surgical simulation; pedicle screw; spine surgery
14	15	0.782	2017	self-healing; zirconium; polylactic acid
15	12	0.878	2015	polymers; kinetic theory; mechanochemistry
16	12	0.964	2017	polymer composites; mechanical properties; fused deposition modeling
17	10	0.912	2016	metals; translation; image-based design
18	5	0.968	2016	humanoid; actuators; manufacturing

* LLRabbreviation of log-likelihood ratio used to achieve the optimal results with maximum coverage and uniqueness [129].

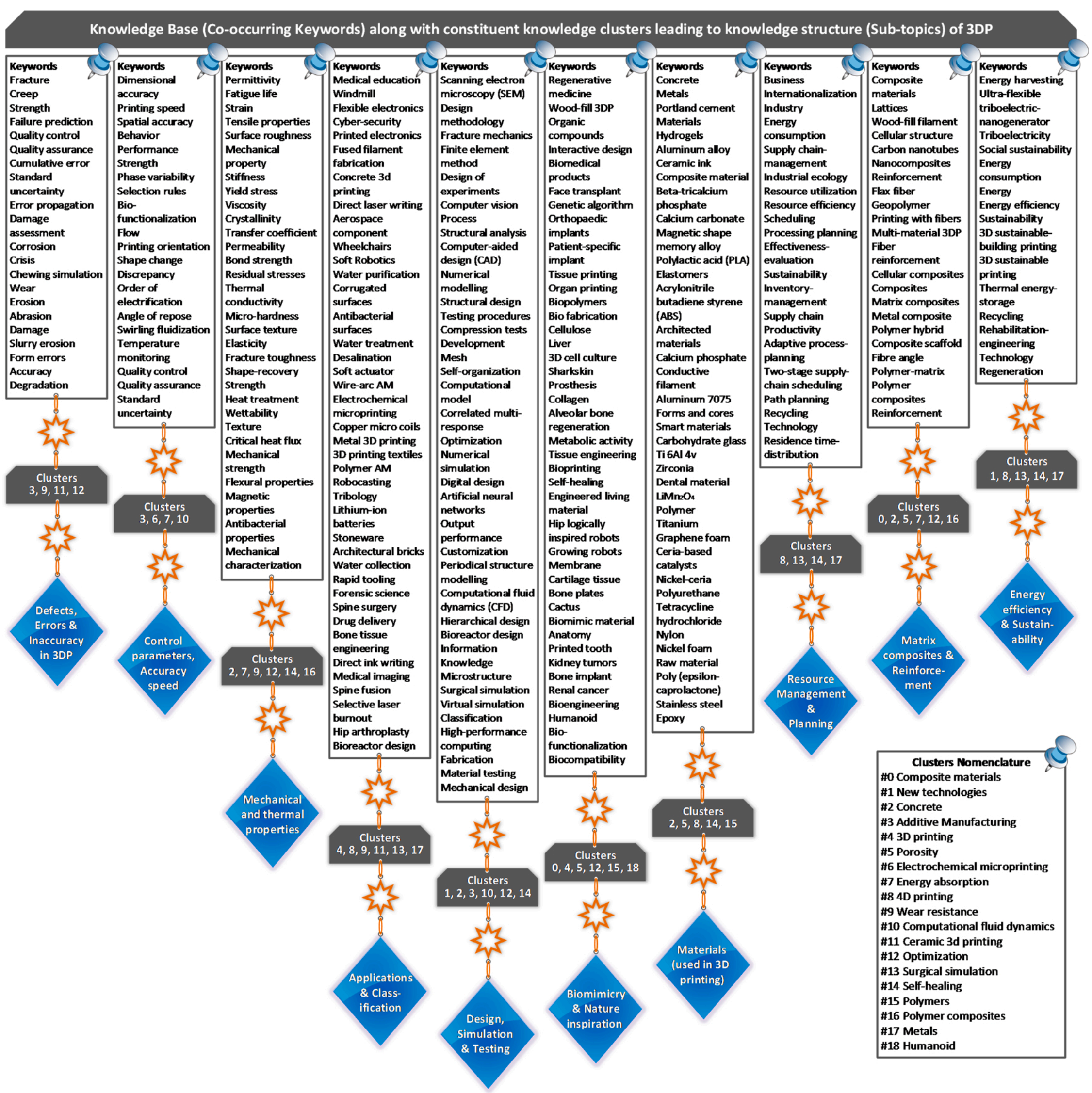

Fig. 18. Knowledge structure map of 3DP-related research on the basis of cluster analysis of co-occurring keywords.

Table 9
Research frontiers of 3DP with the burst strengths, brief introduction, and recent trends.

Rank	Keywords	Strength	Begin	End	Brief introduction & recent trends
1	Fused filament fabrication	3.6239	2019	2020	Also known as fused deposition modelling (FDM). A continuous filament of a thermoplastic polymer is converted into a semi-liquid state by a heated nozzle and extruded on the top of the previously deposited layers to make objects [54].
2	Polymer composite	3.4766	2019	2020	Two types of composites can be studied (i) polymer with polymer composites & (ii) polymer with metal or carbon fiber composites. E.g., composite of carbon fiber in polylactic acid [136], composite of dopamine with carbon nanotubes [139] via 3DP.
3	Rheology	3.2018	2019	2020	Study of the flow of matter, primarily in gas, liquid states or plastic flow of soft solids, under the action of external forces [140]. In 3DP, it is essential to study the rheology of heated materials in a paste form. E.g., the effects of vibrations on the rheology of concrete during 3DP [141], the study of rheology & printability of clay for 3D printed decorative architectural applications [142].
4	Carbon nanotube	2.9154	2019	2020	Widely used in combinations with polymers, metals, and ceramics to form reinforced composite matrices superior in mechanical strength, wear, and erosion. Some examples are polyurethane and carbon nanotube composites based soft pneumatic actuators [143], embedment of carbon nanotubes within Ti-6Al-4 V alloy [85] for aerospace applications.
5	Direct ink writing	2.7378	2019	2020	Used to create materials with controlled architecture and composition, a computer-controlled translation stage causes a pattern-generating device or ink-deposition nozzle to move [144]. Currently, being used to make scaffolds (biomedical engineering) [145], supercapacitor electrodes [146], micro and nanostructures.
6	3DP device	2.6986	2018	2020	Includes all types of 3D printing devices and their feasible products. Some examples are energy storage devices [147], devices for drug delivery [148], prosthetic implants (including hands, arms, legs, organs) [149], microactuators (for soft robotics) [150] and others.
7	Tensile properties	2.4983	2019	2020	Involves the study of mechanical properties, material behaviour of 3D printed objects under fatigue, tensile or compressive loadings. Some common properties are surface roughness [151], stiffness [131], yield stress [132], micro-hardness [134] and fracture toughness [133].
8	Stability	2.4983	2019	2020	Study of stability of the 3D printed parts under thermal, mechanical loading. Recent trends are the enhancement of hydrogel stability with nano clay incorporation [152], investigating melt-pool stability on density & magnetic properties of 3D printed magnets [153].
9	Strength	2.3754	2019	2020	Study of mechanical strength, residual stresses of the 3D printed specimens under various loadings for a wide range of applications. For example, the strength of 3D printed PLA parts [154].
10	Sustainability	2.3648	2019	2020	The priority of the manufacturers and engineers for manufacturing and development of novel technology and customization of the products. For instance, Energy harvesting mechanisms and socially sustainable supply chain innovation through 3D printing.
11	Energy	2.3608	2019	2020	Related to energy harvesting from human-induced or ambient vibrations & energy efficiency of the 3D printed devices. E.g., 3D printed stretchable triboelectric nanogenerator fibers, MEMS vibrational-electromagnetic energy harvester made by inkjet 3D printing.

7. Conclusions

In the current study, the role of 3D printing in the battle against the COVID-19 pandemic is comprehensively discussed, and the sustainability aspects of AM are briefly summarized. The applications of 3D printing related to sustainable and renewable energy harvesting mechanisms were also highlighted briefly. Moreover, a bibliometric study of the three dimensional printing research, published between 1986 and 2021, was established to determine the most influential keywords, knowledge clusters, novel knowledge structure, and research frontiers of 3D printing.

Various applications of AM in the development of renewable energy generation systems and the capability of 3D printing to reduce the intensities of the total energy consumption and CO_2 emissions due to industrial manufacturing by maximally 5% till 2025 reveal the sustainability aspects of AM. 3D printing has also played a versatile role in fulfilling the emergency supplies against the COVID-19 pandemic. Additively manufactured face shields, 3DP-emulsion inks based Respiratory Protective device, biodegradable masks made of PLA, bioprinted ideal tissue model for SARS-CoV-2 infection, and new IT-driven AM-based rapid manufacturing are some of the significant contributions in this regard. During the COVID-19 disease, the market share price and investor interest surged by 70 %, exhibiting an increased demand for the 3D printing market.

From the bibliometric investigation of 3DP literature, the following critical findings were obtained,

(a) The most influential keywords related to 3DP were biomaterials, fused filament fabrication, alloys, tissue engineering, and scaffolds.
(b) The largest knowledge cluster was composite materials whereas, the knowledge cluster comprising the latest research on 3DP was electrochemical microprinting.
(c) The knowledge structure of 3DP consists of ten diverse research themes and various subtopics.
(d) The strongest hotspots in 3DP research are fused deposition modelling, polymer composites, carbon nanotubes (CNTs), rheology, direct ink writing, energy, tensile properties, sustainability, stability, and strength.

The possible challenges incurred by additive manufacturing industry during the COVID pandemic include, manufacturing, safety, certification, design, and legal issues. Despite many profits, the complete replacement of the traditional manufacturing processes by mass production on industrial scale using additive manufacturing is a significant challenge. Moreover, the issues related to thermal stability, lower printing speeds, low mechanical strength, sustainable energy applications, and surface finish, need to be addressed for further augmentation of the 3DP research. Perhaps the applications of 3D printing to develop medium-to-large scale mechanisms for sustainable energy harvesting will be the most desired research domain in the future.

To prevent the COVID-19 pandemic outspread, it is crucial to combine the services of medical professionals with AM technology to promote the associations of 3D printing companies with medical specialists. Moreover, the public facilitation of 3D printing amenities and cheaper materials can encourage the community to contribute to this mission. Engineers and scientists are required to develop relatively inexpensive and readily approachable rapid prototyping technologies, materials, and open-sources CAD designs to deal with emergencies.

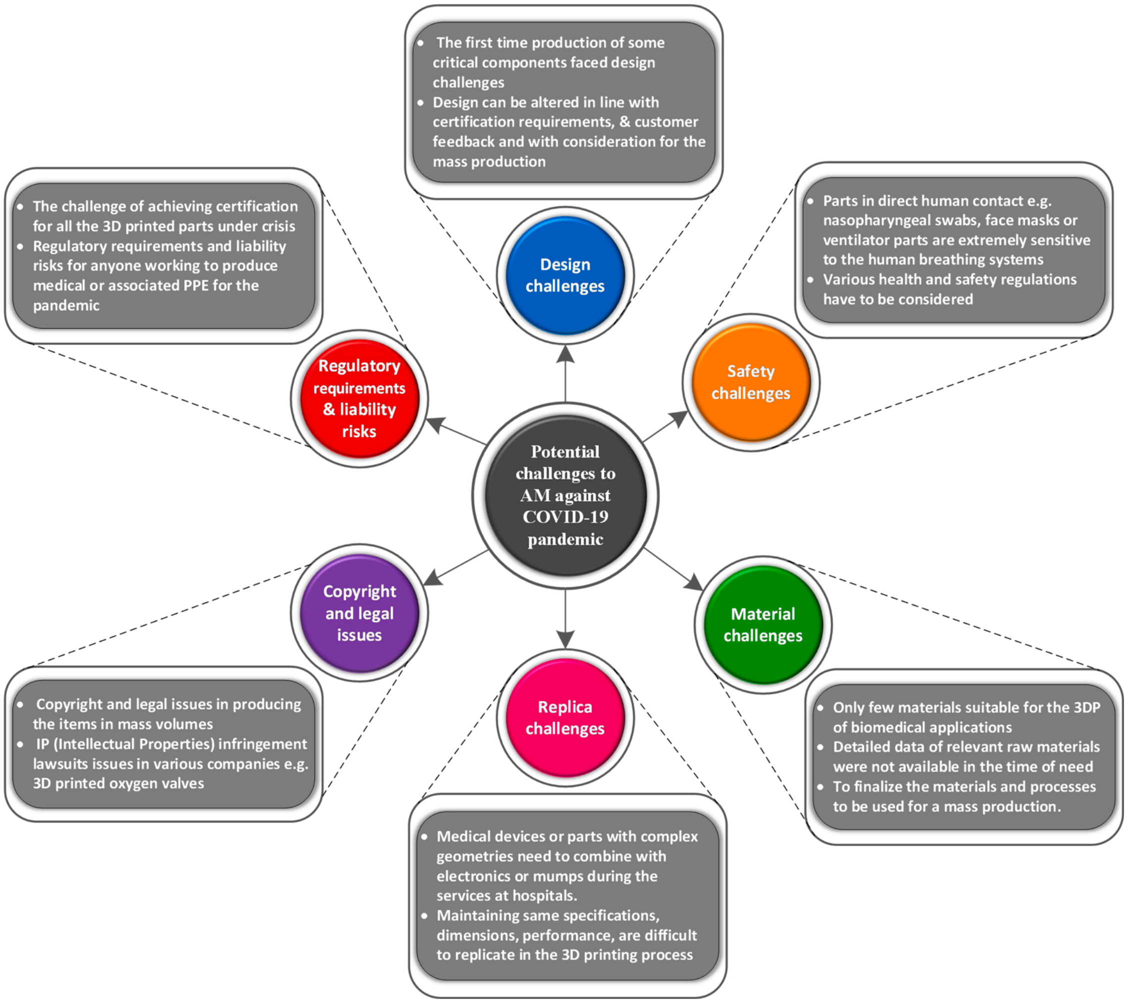

Fig. 19. Potential challenges incurred by additive manufacturing in the fight against COVID-19 pandemic.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jmsy.2021.07.023.

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