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Review

3D Printing Technology for Rapid Response to Climate Change: Challenges and Emergency Needs

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ABSTRACT: Providing rapid, efficient, inexpensive, and resilient solutions is an eminent and urgent need for emergency relief conditions, mainly and increasingly driven by the impacts of climate change. Under such disastrous circumstances, the current practice involves preparation, dispatching and managing significant amounts of materials, resources, manpower, and transportation of basic needs, which can be hindered remarkably by infrastructure damage and massive loss of lives. However, an emerging technology known as 3D printing (3DP) can play a significant role and rapidly bring unlimited innovative solutions in such conditions with much lesser resources to meet the necessities of large populations affected. Considering the recent progress of 3DP technology and applications in different industrial and consumer sectors, this study aims to provide an analysis of the status and current progress of 3DP technology in various fields to understand and present its potential for readiness and response to disasters, emergency and relief need driven by climate change. Secondly, this study also presents a sustainability assessment of 3DP technology for such cases to evaluate economic, environmental, and social impacts. Finally, policies and strategies are suggested to adapt 3DP technology in different sectors to prepare for large-scale emergencies.

Keywords: 3D printing; Additive manufacturing; Disaster; Climate change; Emergency response

1. Introduction

The provision of fast, inexpensive, durable, and resilient solutions is an urgent need for climate change challenges and emergency conditions like severe weather (thunderstorms, hail, tornadoes), earthquakes, fire, chemical and biological emergencies, hazardous material accidents, civil disorder, national emergency (war, terrorism), etc. [1]. For relief groups and governments, providing shelter, accessibility (roads, bridges), heating/cooling, food, water, health services, transport, and communication are essential requirements during and immediately after calamities and disasters. However, existing solutions are slow, expensive, insufficient, or, most of the time, lead to further problems and technical barriers, causing the lack of decent and humanitarian solutions [2,3]. In addition, due to uncertainty, weather, safety, security, and logistical difficulties, the traditional solutions become expensive, time-consuming, and challenging.

3D printing (3DP) refers to a process under the broader terminology of additive manufacturing (AM), where three-dimensional objects are manufactured via material addition contrary to conventional subtractive fabrication [4]. The technology could provide a stronger and more resilient solution to several basic human needs in these conditions. The technology could offer an economical solution to the different needs in such situations through its robust, on-demand, on-site production abilities [5]. The significant and additional benefits and impact of 3DP can be used to act in emergencies and disasters to bring resiliency and sustainability. The emergency, disaster, or pandemic situation results in a surge in price and the unavailability of essential and critical needs by affecting the supply chain and production. COVID-19 is a recent example where 3DP technology has proved its ability to address severe challenges in medical emergencies. Similarly, 3DP technology has been developed to a level that can now be implemented in building fast and affordable housing and other built environment needs like bridges and other critical infrastructure following a

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disaster. Keeping in view the increasing frequency of disasters and emergency conditions and the recent progress in 3DP technology and application, this study aims to:

- Review the status and recent progress of 3DP technology in different fields to understand its abilities in disaster management and climate change emergency conditions.
- Perform the sustainability assessment by evaluating the trade-off between the gains and economic, environmental, and social impact of the technology in emergency conditions.
- Understand the technology's critical factors, challenges, and limitations in adapting to such conditions.
- Analyze the adaptation of 3DP technology in different sectors of life in emergency conditions on a large scale and suggest its policy and adaptation strategy.

The first part of the paper analyzes the review of the applications of 3DP technology in different fields during emergency and disaster conditions. The first section discusses the 3DP applications in the built environment sector, including construction, furniture and household Items. The subsequent section presents the applications of 3DP in the healthcare sector. The third section delivers the 3DP for transportation, logistics, and supply chains, followed by the 3DP for the physiological and social sectors. Finally, a sustainability assessment for 3DP processes is presented along with the conclusions and suggested policies for the role of 3DP in emergencies.

2. 3DP for the Built Environment Sector

Critical infrastructure, such as shelters, bridges, health and education facilities, are directly or indirectly affected in most emergencies and disasters. Food and built-environment facilities are the most vital requirements because they set the stage for others to have a natural, long-lasting impact. Due to uncertainty, weather, safety, security, and logistical difficulties, it is likely also the most expensive, time-consuming, and logistically challenging. Relief and Humanitarian Organizations (RHO) are constantly on the cutting edge during the most challenging calamities and disasters. They are, therefore, coordinated and given authority to achieve the shared objective of providing "assistance" quickly and cheaply in challenging and unpredictable circumstances. Typically, RHOs start every catastrophe or tragedy by offering temporary solutions like tents for shelter and other simple, low-cost ways out. However, the results of these solutions are usually interim and cause several social, health, and economic problems in the long run.

2.1. 3DP for Construction

3D printing (3DP) technology has advanced to the point where it can now be used to create dwellings quickly and affordably using standard or custom construction designs [6,7]. The 3DP has various benefits, including quicker construction, lower costs, and safe working conditions. With its digital production, 3DP presents itself to tackle several issues that the current concrete industry faces. This section explores the transformative capabilities of extrusion-based 3D concrete printing (3DCP) and its applications. Before delving into the intricacies of this digital production method, it is imperative to provide a preliminary understanding of what lies ahead. Figure 1 shows a few illustrations of extrusion-based 3DCP designs for the built environment.

Using this technology, architects may create buildings with unusual geometry that are useful and challenging to construct manually today. Collaborative efforts between architects and engineers become crucial, especially in the aftermath of natural calamities such as earthquakes or mass migrations following conflicts. While engineers, particularly those specializing in civil, structural, and material science, play a central role in developing technical solutions, architects contribute by offering holistic design alternatives. These alternatives address structural considerations and encompass broader social, cultural, and environmental factors. The objective is to create solutions that are not only better, quicker, and less expensive from an engineering standpoint but also culturally sensitive, socially inclusive, and environmentally sustainable. This interdisciplinary approach ensures a comprehensive response to the challenges posed by post-crisis scenarios. A more environmentally friendly building procedure can be produced using the 3DP approach to lessen environmental consequences. Due to a production method that effectively manages construction waste and optimizes material consumption, less post-manufacturing waste is anticipated. The authors argue that if 3DP is redesigned to function during times of emergency and disaster, extra advantages and impacts can be obtained. In their recent studies, the authors presented a similar concept to scale up 3D-printed shelters to permanent 3D-printed villages or communities instead of temporary shelters, Figure 2. These can provide a long-lasting, proper, resilient and sustainable solution to shelter needs in case of emergency conditions. The 3D-printed community can be used for other purposes in normal conditions, such as festivals and the tourism industry.

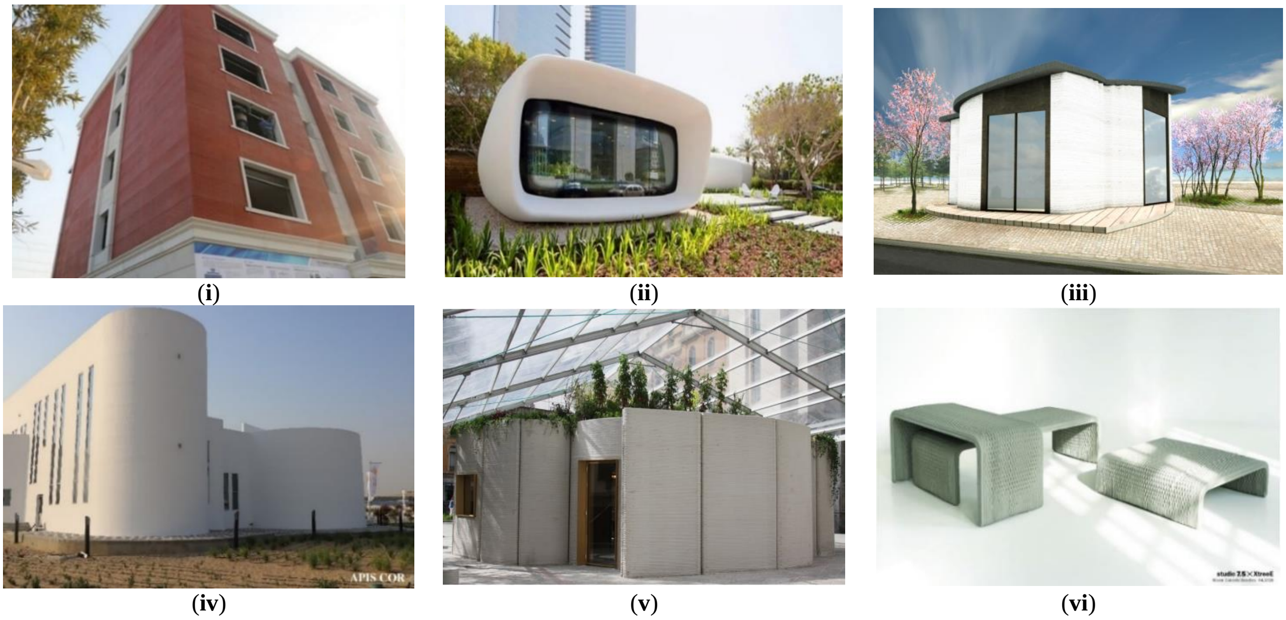

Figure 1. Few real-life practical applications of extrusion-based 3D concrete printing technology. (**i**) 3D-Printed Multi-Story Apartment, Winsun [8], (**ii**) First 3D-Printed Office in Dubai [9], (**iii**) Europe's First 3D-Printed Building [10], (**iv**) Double-Story Administrative Building in Dubai [11] (**v**) 3D Housing 05, Milan [12] (**vi**) Woven Concrete Benches [13].

Figure 2. Architectural solutions and renders of possible single setups of the housings designs for the proposed mobile 3DP system: (**a**) circular, (**b**) hexagonal, (**c**) mixed, (**d**) square, (**e**) Mobile 3DP Village Succession render [14].

Extrusion printing [15], powder Jetting [16] and 3D-printed formwork [17] are three popular 3DP technologies under built-environment applications. Extrusion-based techniques, where considerable material is selectively deposited to generate a layer of selectively cut geometry, are the most popular in the built environment. This process is comparable to the fused deposition modelling (FDM) approach, in which concrete is printed using a robot, a crane, or a gantry 3D printer. Examples of a few commercially available printers are provided in Table 1.

An extrusion-based 3D concrete printing (3DCP) system is placed on a gantry or a robotic arm that accurately positions the printing material filament via a nozzle. The material with a generally high cement content creates freestanding components, free assembly, walls or columns, or permanent shuttering with typically cast structural parts. External support, detachable material, or corbeling may be installed for constructions with significant overhang angles. A gantry-based or robotics-based printing system is employed in 3DP technology for construction. A printing head is attached to the robot, and two peristaltic pumps are in a robotics-based system. The first pump supplies the concrete material, while the second provides the accelerator. A microcontroller manages the two pumps and the printing head together. A hose from the mixer is linked to the printer head in a gantry-based printer. A four-degree freedom mechanism controls the printer head attached to the vertical arm. The printer head has a nozzle connected to it, which is often composed of steel. The binder jetting (BJ) approach is recommended for intricately designed concrete constructions. A binder material is ejected onto a selected powder bed during the BJ to create a two-dimensional (2D) layer. Due to its susceptibility to weather, this technology is rarely used for on-site construction, unlike extrusion processes. Direct 3DP of intricate concrete structures is complex since architectural components have not yet met the requirements for most 3DP methods. 3D printed formwork is employed in this situation. The manufacture of mesh moulds and 3D-printed formwork are the two basic methods in this area. Both approaches start with formwork 3DP; then, the concrete is cast using extrusion-based technology.

Table 1. Extrusion-based commercially available Concrete 3D Printer.

Manufacturer	Model	Process	Type of System	Materials	Capacity (m)	Origin
BETABRAM	P1V2	Extrusion	Gantry Based	Concrete	16 × 8.2 × 3	Slovenia [18]
COBOD	BOD2	Extrusion	Gantry Based	Concrete	1.9 × 2.1 × 1.5 *	Denmark [10]
Constructions-3D	Maxi Printer	Extrusion	Robotic Arm	Concrete	13 × 13 × 10	France [19]
CYBE	RC 3DP	Extrusion	Robotic Arm	Concrete	-	Netherlands [20]
ICON	Vulcan II		Gantry Based	Concrete	8.5 × 8.5 × 2.6	America [21]
MUDBOTS	3D Printer 664	Extrusion	Gantry Based	Concrete	1.8 × 1.8 × 1.2	America [22]
	3D Printer 10108				3 × 3 × 2.4	
	3D Printer 18189				5.5 × 5.5 × 2.7	
	3D Printer 25259				7.6 × 7.6 × 2.7	
	3D Printer 252512				7.6 × 7.6 × 3.6	
	3D Printer 50509				-	
	3D Printer 501009				15 × 30 × 2.7	
TOTAL KUSTOM	Stroy Bot 6.2	Extrusion	Gantry Based	Concrete, Polymer, Ceramics	10 × 20 × 6	America [23]
	Stroy Bot 7.1				10 × 20 × 4	
	Labyrinth 3D				5 × 5 × 3	
	Architect's Printer				1 × 0.5 × 0.5	
WASP	Crane WASP	Extrusion	Delta	Earth-based, Concrete, Geopolymer	Ø 6.3 × 3	Italy [24]

* Custom Configurations offered.

The emergence of 3D concrete printing for emergency infrastructure needs epitomizes a burgeoning field of technological innovation [25]. The pioneering Striatus bridge in Venice and the world's first 3D-printed reinforced, pre-stressed concrete bridge in the Netherlands epitomize the immense potential of 3D concrete printing. Striatus is a remarkable example, showcasing the creation of robust bridges solely relying on compression forces, optimizing material usage for maximal strength. These achievements, involving collaborative efforts from various entities, including Block Research Group, incremental3D, and Holcim, underscore the interdisciplinary nature driving advancements in this technology. Similarly, the Dutch bridge's inauguration emphasizes the inherent adaptability and versatility of 3D concrete printing, heralding a new era in structural engineering and construction methodologies [25,26]. Further illuminates this landscape, addressing key lacunae in the field [27]. Noteworthy studies published in the Springer journal "Architecture, Structures and Construction" and the RILEM Bookseries delve into specific instances, including a 3D-concrete-printed, mortar-free, unreinforced masonry arched footbridge and a topology-optimized 3D-printed concrete bridge [28]. These scholarly endeavours strive to fill critical gaps, such as the deficiency in design tools tailored for large-scale 3D concrete printing, thereby emphasizing the transformative potential of this technology within the construction industry [27,28]. Furthermore, parallel research inquiries encompassing structural reinforcement systems and the broader application of 3D printing technology in construction significantly enhance the understanding and application of 3D concrete printing methodologies for bridge construction in emergency scenarios [29]. These collectively delineate the advancement trajectory in 3D concrete printing for bridges, underpinning it's evolving significance in emergency infrastructure deployment.

The adoption of 3DP technology depends heavily on its economic viability because the building sector is cost-sensitive [30,31]. Numerous studies have suggested that 3DP technology in concrete construction will be economically viable and highly productive [32–34]. Numerous websites and weblogs (such as www.3ders.org) have reported lower construction costs. For instance, WinSub reported a \$4800 cost for a 200 m^2 or so 3D-printed house, significantly lower than the same home built conventionally [35]. Research on the economic viability of 3DP technology for concrete buildings is ongoing [36]. Although the capacity to cut costs is a vital component of automation in any business, it is unknown whether 3DP technology is economically viable in disasters and emergencies. Although several studies have looked at how 3DP technology might be improved for the construction industry, the topic is still in its infancy regarding material development, project size, and total project cost [37]. Existing literature has significantly contributed to the understanding and advancement of 3D printing technology in construction and structural engineering. Notably, studies such as [38] offer a comprehensive overview of design parameters, mix properties, robotic technologies, and reinforcement strategies, providing valuable insights into improving 3D printed structural elements. Moreover, [39] critically evaluates various 3D printing techniques in construction, shedding light on their benefits, challenges, and associated risks, enriching the discourse on this technology's applicability. Additionally, research like [40] delves specifically into the structural compositions of cement-based materials used in 3D printing, contributing essential knowledge to the material science aspect of this field. Another area largely unknown in nearly every phase, including design, process technology, and material, is the environmental effect and life cycle evaluation of 3DP technology for construction [41–45]. Several previous reviews have discussed the overall technological consideration, potential, and material development of 3DP systems for the building [46–50]. However, to lessen future difficulties, evaluating the technology's sustainability is crucial—energy use, environmental impact, and prospective prospects.

2.2. Furniture and Household Items

Unveiling a new era in furniture production, 3D printing (3DP) technology stands poised as a transformative force, particularly in disaster management operations. Transforming people to safe places is often required in an emergency, and temporary shelter camps are produced for this purpose. The need for daily household items rises as transportation and markets are greatly affected. 3DP technology can be a localized solution, as household items and basic furniture supplies can be fabricated using this technology (Figure 3). Waste materials can be an excellent source of abundant materials on disaster sites for fabricating and producing 3D-printed furniture. However, there are some constraints and problems in making furniture using these techniques, such as surface finishing, mechanical properties of materials, assembly of furniture components, and production capabilities. Studies are underway on producing furniture and other household items using 3DP techniques. One of the examples of fabricating furniture from waste materials is waste plastic bottles. Recycled plastic bottles are a great source of producing 3D-printed furniture.

Figure 3. (**a**) Laser Printed Trabecula Bench [51]; (**b**) 3D Printed Stools [52]; (**c**) 3D Printed Sofa Chair [53] (**d**) 3D Printed Seat [54] (**e**) 3D Printed Sofa [55] (**f**) Puzzle Chair [56].

Recycled PET can significantly contribute to the production of 3D-printed furniture, which will also help to control environmental pollution, and manufacturing costs will be substantially reduced. The procedure starts with collecting used bottles at recycling facility centres or by placing recycle boxes in public places to collect plastic waste [57]. Then, the plastic waste materials are broken down into small pellets using crushers. These pellets can be evolved directly into the extruder nozzle of the 3D printer or can be used to produce filaments for the 3D printer. 3D printers, in this context, facilitate form production in a virtual environment. Software programs like 3DS Max, Maya, SolidWorks, and other CAD software can be used to draft the form of furniture virtually before physically moulding the furniture. Startups like [58] have given people access to workshops to bring waste plastics and print their recyclable objects. Plastic materials such as utensils, buckets, and other items can be fabricated using waste materials and 3DP.

3. 3DP for Healthcare

The flourishing 3DP technology has overcome many biomedical device manufacturing challenges. A range of biocompatible and biodegradable materials, including polymers and metals, can be manufactured by 3DP [59,60]. Rapid prototyping with customized fabrication and low waste makes 3DP one of the most favourable techniques for the healthcare system in critical emergencies. 3DP provides quick prototyping, customized manufacture, and little waste when all three factors of time, on-demand production, and materials cost are high priorities in emergency and pandemic conditions.

3DP has shown a growing interest in the biomedical field due to its complex design-making capabilities, which are otherwise highly challenging with traditional manufacturing [61,62]. This ease of use gives immense freedom in manufacturing complex medical devices. 3DP technology has contributed to the medical field by producing medical equipment customized at a lower cost to fulfil the demand-supply limitations [63]. There are multiple examples in the past, but the current COVID-19 is a recent experience that has affected the global supply chain system. Covid-19 has immensely affected civil aviation globally, where about 7.5 million flights have been cancelled worldwide to curb the spread of COVID-19 [64]. This cancellation of flights has also affected the delivery of medicine, crucial medical equipment, and personal protective equipment (PPE) for the protection of frontline medical workers and patients. This shortage must be tackled by introducing 3DP technology to reduce import dependency and overcome the demand and supply gap. The most popular products produced via 3DP during the pandemic are face masks (as shown in Figure 3), face shields, goggles, nasal swab kits, and venture valves. 3D printing provides customized product design in real-time and on-site product production. 3D printing involves image scanning and making a computer-aided design (CAD) model. This CAD model is then converted into an STL file, which is then provided to the slicing software. The software converts the images into slices, and the 3D printing is carried out layer by layer [65–67]. The 3D printing processing is depicted in Figure 4.

Due to cargo flight restrictions and lack of delivery, 3DP has been used for manufacturing medical devices and PPE [68]. The frontline medical workers, patients, and the public used protective equipment to safeguard themselves from the infectious droplets in the air and during patient interactions. Prusa (an FDM manufacturer in the Czech Republic) donated about 200,000 3D-printed face shields to medical professionals and practitioners [69]. Similarly, Etihad Airways, in collaboration with its medical wing, manufactured 3D-printed face shields using recycled plastic and distributed them to hospitals in UAE [70]. Furthermore, 3D-printed frames as replacements for defective and broken bands for N95 and KN95 ensured a longer life for these masks. Other than masks, protective eyewear was manufactured using 3DP technologies. A 3D-printed frame (Figure 5) for protective goggles was designed by Boltian, a Spanish designer, where the lenses can be inserted easily [71].

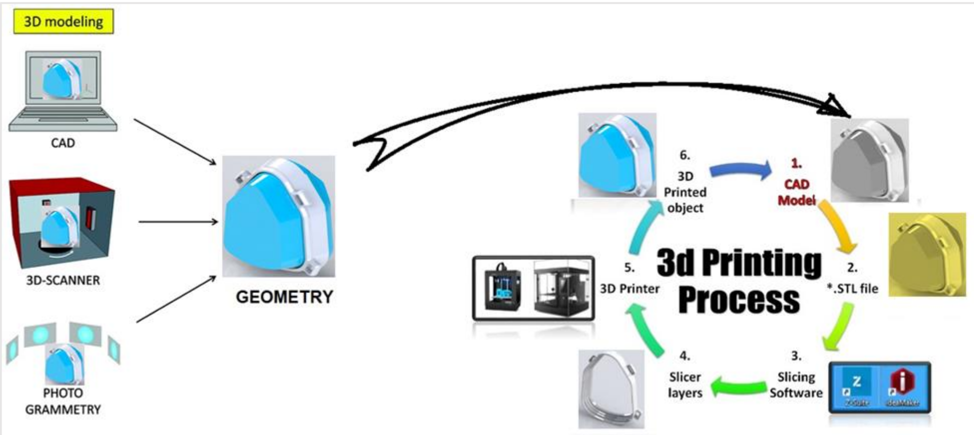

Figure 4. Pathways for customized facemasks using the 3DP technique adopted from [72,73].

Figure 5. Components of 3D printed goggle frame for protective eyewear [71].

Besides protective wear, 3DP is a promising technology for making other medical accessories. Mechanical ventilators were one of the essential secondary components needed worldwide. During the COVID-19 pandemic, most automobile companies started manufacturing ventilators using 3DP technology. During the pandemic, 3D-printed ventilator valves were in high demand to support patients with difficulty breathing. Isinnova, an Italian engineering startup, designed a ventilator valve known as a venturi valve (as shown in Figure 6), which proved to be a life saviour in Italy [74]. Isinnova also designed a 3D-printed connector valve for easy breathing purposes. The ventilator splitter is another example of the 3DP manufactured product, which hugely benefited the circumstance by providing oxygen from a single ventilator to multiple patients. One of the mandatory protocols by WHO for COVID-19 patients is to isolate them [75]. With the higher number of patients, it was becoming extremely difficult for healthcare units and hospitals to isolate the patients lacking facilities. In this situation, producing transitory dwellings was a massive achievement in quarantining the patients. The 3D-printed mobile ward production was quicker and played its part in an emergency [76,77].

The life span of the COVID-19 virus varies from 3 h in airborne droplets to 72 h on stainless steel and plastic surfaces. To prevent direct contact with these surfaces and avoid cross-contamination, Materialize (Belgium) introduced a 3D-printed door opener and button-pusher (as shown in Figure 7) [78]. The Covid-19 test kit was yet another high-demand tool to confirm the infection during the pandemic. The sample for testing is usually collected using a nasal swab. Initially, there was a shortage of swabs, which was resolved quickly with the help of 3D-manufactured swabs. The 3D-printed swabs were more efficient in terms of flexibility and durability and were more user-friendly to medical professionals [79].

3DP is an innovative technology that has revolutionized various biomedical manufacturing needs. 3DP has revolutionized biomedical engineering as a promising new technology by manufacturing complex structures customizable at low cost with easy fabrication and rapid manufacturing processes. These printers can be stored at home, in industry, and in educational institutions and used by students and researchers. 3DP using bioactive materials can be of enormous importance for handling future pandemics. Not only for emergencies, but 3DP has a considerable contribution to medical implants, and various organs can be 3D-printed based on patient anatomic data. Considering the disaster and pandemic conditions where the unavailability of labour, resources, logistics, and price surges are significant challenges, 3DP has become an economical solution for producing many biomedical supplies, equipment, and devices.

Figure 6. An Italian engineering startup created a 3D-printed venturi valve to help patients with difficulty breathing. (Image taken from: https://www.bbc.com/news/technology-51911070).

Figure 7. 3D-printed door opener (**A**) and button-pusher (**B**) to avoid touching surfaces [78].

4. 3DP for Transportation, Logistics, and Supply Chains

3DP processes can provide a rapid response in the case of emergencies such as disasters, floods, earthquakes, or any other mass destruction activity. These processes can be essential in undisturbed transportation, communication, logistics, and supply chains, especially in emergencies. 3DP has recently evolved as an alternative manufacturing route for different industrial sectors [80–82]. The progress and development of these processes over the past few decades have been so rapid that few experts claim that these technologies will probably lead to the third industrial revolution [83–85]. The above claim is supported by substantial adaptation of 3DP technologies in the automotive and aerospace industry [86–88], household products [89], biomedical engineering [90–92], and rapid prototyping applications [93]. We present the current literature focusing on the impact of 3DP processes on logistics, supply chains, and transportation.

4.1. 3DP for Logistics and Supply Chains

The working principle of the 3DP processes strongly impacts the different parts of society, including transportation, communication, and logistics. The streamlined logistics networks and simplified scheduling facilitated by 3DP can play a pivotal role in efficiently responding to and managing crises, such as the challenges posed by global emergencies. Due to the unique qualities of 3DP processes, the fabrication of highly customized parts with lesser post-processing steps has positively impacted supply chain designs and implementation [94]. 3DP methods promise to switch to decentralized manufacturing and supply chains rather than the current centralized systems [95–97]. Decentralized manufacturing can contribute to transporting goods, supply chains, and business models of the associated companies [98–100]. The impact of 3DP has been investigated regarding future possibilities and qualitative impacts on society and future business models [101–103]. The focus is mainly paid to using material and energy in terms of the sustainability of these processes [104]; however, its role in goods transportation is merely discussed. This section delves into the profound implications of 3DP on logistics, shedding light on its promise to transition from centralized to decentralized manufacturing and supply chains.

Regarding logistics, the adaptation of 3DP technologies is mainly studied for companies, leaving a substantial impact on manufacturing capacity and goods transportation [105–107]. The scope of 3DP processes will ultimately reach international adaptation and affect the current global industries' layout [102]. Consequently, current manufacturing activities in Asia will flow back to European countries and the US, taking out the leverage of cheaper labour in Asia as lesser human resources are required to work with these processes [107]. In addition, local 3D printers will eliminate the cost of import duties on 3D printers and technical constraints in these regions. With the advancements in 3DP materials, the cost of 3DP materials will ultimately reduce over time, resulting in further public acceptance of these processes. In addition, due to the working principle of 3DP processes, the material utilization for manufacturing will decrease significantly, reducing the global trade volumes and shrinking the logistics network [108]. In the era of the 3DP industry, complex JIT distribution or complex material management is not required anymore, and worldwide logistics scheduling will be way more straightforward. The current logistics service providers should adopt this transition to compete with their competitors. A case study on a prominent logistics company (UPS) was performed, and it was analyzed that this service provider is transitioning towards 3DP circumstances [109].

Given the existing literature, there is a need to obtain more insightful impacts of 3DP processes on goods transportation, logistics, and supply chains. In addition, the potential positioning of 3DP facilities to take over the existing manufacturing process should be explored [110]. The reported literature in this field also lacks a systematic model on the impact of 3DP processes on goods transportation, logistics, and supply chains. Future studies should focus on and cover different domains where adaptation of 3DP can affect, such as transportation security, positioning of 3DP facilities, ease of access, ecological impacts, infrastructure demands, public prosperity, revenue, employment, consumption relationships, and satisfaction [111,112]. It is also advised that the countries involved in the materials processing should transform the logistics amenities, and cooperation with relevant countries should be developed to cope with the challenges of 3DP [113]. Logistics companies must reform their inventory structure to respond rapidly to customer requirements [109]. In addition, the warehouses should also acquire a variety of 3DP materials to provide immediate order manufacturing and avoid delays or shortages. These advancements in adapting 3DP in logistics and supply chains can positively contribute to global emergencies (like COVID-19).

4.2. 3DP for Transportation and Communication

Unmanned aerial vehicles (UAVs) have been employed in various applications like remote sensing, wildlife research, agriculture, photography, oil spill detection, surveillance, offshore inspections, and delivery systems [114–119]. In this regard, drones can monitor disaster-affected zones where the human presence to carry out escort or development missions is impossible [120,121]. The applications of drones in such activities require acquiring a large amount of data, and longer flight times are desired. Therefore, there is an eminent need to produce lightweight structures to achieve significant weight reduction using structural optimization [122]. Several researchers have made efforts in this regard; for instance, Ferro et al. [123] proposed a design methodology to produce lightweight drones for speed competitions using the 3DP process, as these processes can provide a high degree of personalization. The 3DP fabrication of lightweight drone frames is also possible using continuous fiber reinforcements to polymeric materials [124], as shown in Figure 8. In addition, the flexibility provided by 3DP processes offers new routes for innovative design of such structures, such as bioinspired structures. Henderson et al. [125] demonstrated the lotus blossom-inspired 3D printed ground launchable and air deployable (GLAD) drone capable of changing streamlined projectile shape into a multirotor, as shown in Figure 8.

The drones can provide emergency response services for surveillance in disaster-affected zones, delivery of basic amenities (food, clothing, etc.), construction of rapid liveable space, and much more. In 2014, in collaboration with Google, drone industry experts tested thirty flights in Queensland, Australia [126]. The test flights were carried out to deliver first-aid kits, dog food, candy bars, and communication radios. Google is also working on its drone strategy to include medical products for such situations. Such test trials are being carried out globally, especially after COVID-19, when the world has faced a prolonged disturbance in communication and transportation. However, 3DP processes can play a critical role in such cases, as the continuation of such activities is possible with such UAVs in disastrous situations. Based on the existing literature, there is an evident need to explore innovative design strategies and materials to carry out mass emergency operations with the help of drones. Currently, available solutions can carry a minimal amount of supplies; however, the applications of UAVs in emergencies to carry abundant supplies should also be considered and explored.

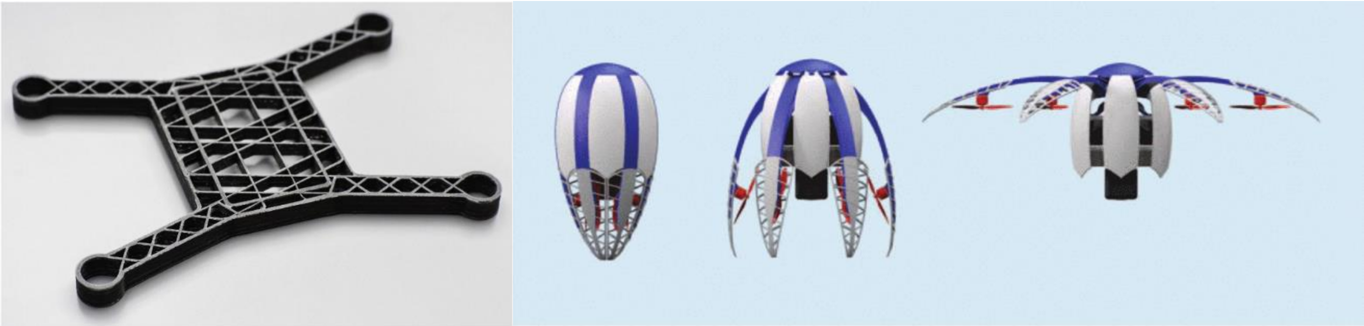

Figure 8. 3D Printed Drone Frame Fabricated Using Continuous Fiber-Reinforced Composites [124] and Configuration of 3D Printed GLAD Drone [125].

5. 3DP for Physiological and Social Sector

In addressing physiological and social needs during emergencies, 3D printing (3DP) stands out as a transformative force, offering innovative solutions. Water security, a critical disaster concern, finds answers through 3DP applications, producing infrastructure, membranes, and filtration systems. Simultaneously, 3DP is vital in maintaining air quality and creating environment-friendly systems, air filters, and sensory lamps. Expanding to clothing and footwear, 3DP integrates with garment simulation, showcasing potential in disaster management apparel. In food security and agriculture, 3DP streamlines operations, reduces stockpiles, and ensures local production, enhancing food security. These applications highlight 3DP’s pivotal role in meeting physiological and social needs and providing necessities during uncertain and challenging situations. This section highlights using 3DP technology for physiological and social needs during these emergencies. By effectively using this technology, we can help provide necessities to the people in need in these uncertain situations.

5.1. 3DP for Water and Water Infrastructure

Disasters often result in a shortage of supplies and aid. Surveys have depicted that the demand for clean water will rise by 400% in the next 30 years [127]. As 3DP technology has been increasingly used in water applications, its use in disasters and emergencies can efficiently solve the water security problem. In addition, the role of 3DP can be used efficiently to produce 3D-printed innovative structures that make the thermal desalination process more energy efficient.

In addition to various other benefits offered by 3DP, water purification and desalination companies are shifting toward this technology. They are trying hard to incorporate 3D printers into their manufacturing process. Some companies, like Nano Sun in Singapore, produce membranes for water treatment and filtration using 3DP technology [128]. Thermal desalination plants require massive fossil fuel resources for heating purposes, and energy availability in emergencies is challenging. Solar thermal desalination and distillation plants operate on the principle of solar absorbance. They can better use off-grid water production in disasters and emergencies [129]. Researchers have created 3D-printed devices from carbon-based nanomaterials to improve solar absorbance and energy efficiency for thermal desalination. Research has also been carried out to produce enhanced composites. For instance, [130] developed pastes involving carbon nanotubes (CNTs) and graphene oxide (GO) to fabricate 3D-printed materials for the enhancement of solar desalination plants. 3DP technology can also be used for sanitation services, various water collection systems, and numerous treatment infrastructures. 3D-printed filtration systems are also evolving, and water is purified through these systems. Similarly, 3D-printed water tanks are also being produced, which has aided our water collection systems.

5.2. 3DP for Air Quality

3DP technologies can also be used for environmental stability. It can control air quality and several other factors in disaster management. Air quality levels are of great importance in emergency conditions such as wars, biological wars, disasters, and pandemic situations. To save people from these conditions, they are placed in closed places, and maintaining the air quality levels in such areas is essential. In the cases of pandemics, closed public spaces must be declared germs-free, and this can be possible by employing 3DP technologies. Studies are underway to produce environment-friendly systems to control air quality levels. Salamone et al. fabricated nano environment-friendly systems to maintain indoor air quality [131]. The system utilized Arduino boards and some sensors that produced low-cost 3D printed systems. Wang et al. developed another 3D fabricated system for monitoring the level of particulate matter in the air [132].

In addition, 3DP can be used to fabricate filters to remove environmental pollutants. Xu et al. contributed by developing an air filter to remove the quantity of nitrogen monoxide from the air [133]. Results proved that it removed 52.6% of NO from the air using this filter. Such 3D fabricated nano-systems can be placed in closed public places to monitor indoor air quality. Companies like [58] manufactured 3D components for a sensory lamp that monitors air quality. The lamp consisted of various LEDs, signalling that the air quality had risen above the threshold levels.

5.3. 3DP for Clothing and Footwear

Applications of 3DP processes are widely spreading in almost every field of life. The number of materials fabricated using 3D printers is increasing, and their availability is becoming more accessible. The evolution of computer graphics and 3D technologies has altered textile design. Designs made on computer systems can be easily converted into garments using 3D printers. As we have seen, the applications of 3DP technology in disaster management can also be used for clothing and footwear in such scenarios. This section will highlight how this technology is evolving for disaster management operations in this sector.

The process of 'garment simulation' has evolved in recent years. We can interlink this process with 3DP technology. Initially, a 3D model of a human body is designed on a computer system known as the virtual model of the human body. Then, using the 3D printer, this model is fabricated, and garment fit evaluation is done. Different studies exist on utilizing 3DP technology in this industry [134]. To increase the quality of fabrics, 3D-printed items are fabricated using advanced materials, enhancing their mechanical properties. Richter et al. created new designs, accessories, and extensions with 3DP technology [135]. They also found it often leads to poor adhesion when 3D-printed objects are combined with fabrics. Grimmelsmann et al. studied the mechanical properties, such as the bending stiffness of the textile, using the 3DP technology [136].

Companies like Pringle of Scotland have used 3DP technology in their industry and produced ready-to-wear clothes and shoes [54]. Researchers at Loughborough University want to make complete 3D-printed dresses and footwear using this technology to revolutionize the clothing industry through 3DP techniques. They can offer 3D-printed clothes and shoes commercial status to all the brands, retailers, and manufacturers worldwide to implement this technology as part of their production process [54]. So, all these benefits can be linked to producing enhanced 3D-printed textiles and footwear.

5.4. 3DP for Food Security and Agriculture

Emergency and disaster conditions also affect the supply chain of different agricultural products, for which 3D printing could provide a viable solution. Supply chains will be streamlined when 3D printing is included in the primary and secondary agriculture industries. Products will be printed as needed, which will shorten lead times for consumers, reduce the amount of stock kept in warehouses and retail storage, and reduce the amount of physical mould inventory producers must keep on hand [137]. The use of 3D printing in agriculture, food processing, and environmental monitoring and protection is discussed in the paper [138]. The most common thermoplastics used in agriculture are PLA and ABS. Food is directly extruded, enabling those with trouble swallowing to eat more.

Chains, gears, shock absorbers, seeder components, and harvester attachments are just a few of the agricultural items that may be replicated with 3D printing. With new printing materials, printing parts and components from sturdy plastics to metal and alloy combinations is now possible. 3D printing can increase agricultural operations' efficiency since customized components can be created and supplied locally, reducing downtime. There will be numerous uses for 3D printing in agriculture with time and innovative thinking [137]. There will be numerous uses for 3D printing in agriculture with time and innovative thinking.

Food is a necessity of life after a disaster has struck any region. Having reliable access to enough nutritious food is disturbed during these emergency conditions. Natural disasters significantly impact food security, impairing agricultural production, availability, and accessibility to good food. 3DP technology has also proved its worth in the food industry. We can print edibles using 3D printers, as this technology can be used to tackle dietary issues. 3D printers are portable and can be carried to far-flung areas that have been affected due to disasters.

Studies are underway on creating micronutrient tablets mixed with carbohydrates such as grains, cereals, and rice [139]. Studies exist on 3DP food, such as chocolate, and dairy products, such as cheese and sugar through 3DP. Edibles can be printed through different 3DP techniques, such as extrusion, binder jetting, and inkjet printing. The extrusion-based process includes loading raw materials into the extruder and creating 3D-printed food layer-by-layer. Cheese and dough are the type of food fabricated using 3DP technology. The possible use of this technology in the baking industry was demonstrated in another study [140]. Yang et al. developed 3D-printed food constructs using the lemon juice gel system [141].

Inkjet printing is used for filling surfaces or decorating foodstuff. It uses a stream of droplets to decorate bakery items such as cakes and cookies. The inkjet printer typically works with low-viscosity materials; hence, it cannot create complex 3D food structures. Cheese, meat paste, chocolate desserts, and doughs can also be made using inkjet. The binder jetting technique uses binders to bond layers of powders. This technique is extremely fast in production speed and automatically includes support structures during layer synthesis. However, the binder must have low viscosity to prevent nozzles from spreading [142].

6. Sustainability Assessment for 3DP

With the escalating frequency of both natural and human-induced disasters and their profound impact on human life, there is a growing anticipation of new initiatives to address the challenges posed by such emergencies. 3D printing (3DP) emerges as a resilient and versatile solution applicable across various sectors, including sheltering, built-environment, health and medicines, logistics and communication, and social services during crises.

6.1. Regional Manufacturing Technologies and Flexible Production

Implementing 3DP solutions relies on regional manufacturing technologies, allowing crucial components to be produced precisely where and when needed [143]. This approach overcomes logistical, transport, and delivery time challenges and minimizes the demand for a large workforce. The simplicity and affordability of the 3DP system stand out, providing economic outputs while avoiding the cost inflation triggered by disruptions in the supply chain during emergencies.

6.2. Environmental and Carbon Footprint Advantages

In addition to the inherent environmental benefits of 3DP systems, such as minimal waste generation, they contribute to lower carbon footprints due to localized manufacturing and reduced transportation requirements. The ability to produce different components from the same material enhances efficiency, and the compatibility with renewable energy generation systems further reinforces the environmental sustainability of 3DP technology.

6.3. Social Empowerment and Collaborative Development

Beyond its technical advantages, 3DP technology is pivotal in empowering local labour and communities. By involving affected individuals in the collaborative development of solutions that cater to their specific needs, 3DP builds social and physical capacities, providing urgently needed assistance swiftly and cost-effectively and fostering resilience within communities.

6.4. Rapid Deployment and Instruction

One of the strengths of 3DP technology lies in its ease of use. Individuals can design and fabricate essential components with minimal instruction as soon as needed. This rapid deployment capability is crucial in emergencies where time is of the essence.

6.5. Challenges and Considerations

While 3DP technology holds promise for resilient infrastructure development during emergencies, certain challenges must be addressed. Ensuring the public is well-versed in 3DP technology before emergencies occur is essential. Education and training initiatives should be implemented to equip individuals with the necessary skills and knowledge. Efficient storage of required materials and energy resources for critical conditions is crucial. Strategies for maintaining a readily available supply during emergencies must be developed.

6.6. Evaluating Sustainability and Economic Viability

To comprehensively assess the sustainability and economic viability of 3DP in emergency scenarios, established assessment methods like Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) should be applied. These methodologies offer insights into the environmental impact, cost-effectiveness, and feasibility of 3DP processes and material costs during emergency response and recovery. While 3DP technology presents an ideal solution for resilient infrastructure development in critical situations, ongoing research and rigorous assessment methods are essential to optimize its application and address potential challenges.

7. Conclusions and Suggested Adaptation Policy

This study comprehensively reviews how 3D printing (3DP) has transformed consumption and production in disaster management operations. The overview encompasses developments in water infrastructure, clothing, food security, air quality, furniture, household items, the built environment, and logistics supply chains using 3DP. Despite the transformative potential, several obstacles exist. Ongoing investment is crucial to address technological challenges, and increased market potential could make this more feasible.

Governments and societies could adopt the technology as a responsive adaptation policy to prepare for severe weather (thunderstorms, hail, tornadoes), earthquakes, fire, chemical, biological emergencies, hazardous material accidents, civil disorder, and national emergencies (war, terrorism).

Continuous and strategic investments are imperative to overcome potential challenges in integrating 3D printing (3DP). With a growing market potential, the feasibility of conquering technological hurdles becomes more promising. Governments and societies are strongly encouraged to embrace 3DP as an integral component of adaptive response policies, fortifying their preparedness for various emergencies, ranging from severe weather events to national crises. The recommended adaptation policy entails a systematic and comprehensive approach:

Risk Analysis and Needs Assessment: One fundamental step involves meticulously evaluating risks and needs across various sectors during emergencies. This process aims to pinpoint specific roles where 3DP technology can make a substantial contribution, tailoring its application to the unique demands of each sector.

Policy Design: An essential aspect of the adaptation policy is the development of tailored policies that strategically leverage 3DP technology. These policies should be intricately designed based on a meticulous analysis of expected disaster conditions and the corresponding needs of the affected population.

Technology Access and Literacy: To ensure widespread adoption, there is a critical need to promote technology access and literacy. Making 3DP technology readily available in common places fosters learning opportunities and encourages its incorporation into various aspects of daily life.

Establishment of Emergency 3DP Centers: A key infrastructure component involves establishing authorized 3DP centres equipped with diverse printers. These centres should be strategically designed to meet the capacity requirements of various sectors, including healthcare and the built environment.

Critical Component Preparedness: As a proactive measure, critical components must be pre-designed and readily available for distribution to the public and designated print centres during urgent situations. This ensures a swift and efficient response to emerging needs.

Energy and Material Planning: Proper planning for energy and material availability in critical conditions is paramount. This includes designing and implementing renewable energy systems for sustained operation, coupled with maintaining ample material stock to meet unpredictable demands.

Self-Sustaining Solutions: For long-term viability, the suggested policy advocates using 3DP centres for localized production, supporting various sectors without burdening society during normal conditions. This approach fosters self-sufficiency and resilience.

Educational and Recreational Use: Maximizing the utility of 3DP centres involves leveraging them for educational and recreational purposes. These centres become valuable assets for schools, colleges, and the broader community, contributing to enhanced learning and engagement.

Crowdfunding for Sustainability: Implementing crowdfunding mechanisms is proposed to ensure sustainable financing. This strategy allows the public to contribute to the hosting and maintaining of 3DP centres, making technology accessible and supporting regular operations.

By systematically integrating these elements into an adaptive response policy, governments and societies can harness the full potential of 3DP technology, creating a resilient framework for emergency preparedness and response.

The manuscript suggests exploring a comprehensive cost analysis across sectors during disasters for future research in this field. This includes delving into sector-specific challenges and tailored solutions integrating quantitative data to fortify discussions. Further studies should showcase empirical cases highlighting successful 3DP implementations in underdeveloped regions. Additionally, evaluating policy implementation strategies, assessing the social impact of 3DP adoption, and examining public awareness programs and educational initiatives in disaster-stricken areas are crucial for further investigation.

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References

1. Khan SA, Al Rashid A, Koç M. Adaptive response for climate change challenges for small and vulnerable coastal area (SVCA) countries: Qatar perspective. *Int. J. Disaster Risk Reduct.* **2023**, *96*, 103969.
2. Doll C, Trinks C, Sedlacek N, Pelikan V, Comes T, Schultmann F. Adapting rail and road networks to weather extremes: case studies for southern Germany and Austria. *Nat. Hazards* **2014**, 72, 63–85.
3. Hallegatte S. Strategies to adapt to an uncertain climate change. *Glob. Environ. Change* **2009**, *19*, 240–247.
4. Al Rashid A, Koç M. Fused filament fabrication process: A review of numerical simulation techniques. *Polymers* **2021**, *13*, 3534.
5. Al Rashid A, Ahmed W, Khalid MY, Koç M. Vat photopolymerization of polymers and polymer composites: Processes and applications. *Addit. Manuf.* **2021**, *47*, 102279.
6. Khan SA, İlcan H, Aminipour E, Şahin O, Al Rashid A, Şahmaran M, et al. Buildability analysis on effect of structural design in 3D concrete printing (3DCP): An experimental and numerical study. *Case Stud. Construct. Mater.* **2023**, *19*, e02295.
7. Imran R, Al Rashid A, Khan SA, Ilcan H, Sahin O, Sahmaran M, et al. Buildability Analysis on Squared Profile Structure in 3D Concrete Printing (3DCP). *Eur. J. Mater.* **2023**, *3*, 2276443.
8. Winsun. World's First 3D-Printed Apartment Complex. 2015. Available online: https://weburbanist.com/2015/01/20/made-in-china-worlds-first-3d-printed-apartment-complex/ (accessed on 29 August 2023).
9. World's First 3D-Printed Office Building Unveiled in Dubai. Available online: https://weburbanist.com/2016/05/26/worlds-first-3d-printed-office-building-unveiled-in-dubai/ (accessed on 2 November 2019).
10. COBOD. 2018, BOD2. Available online: https://cobod.com/bod2/ (accessed on 29 August 2023).
11. Apis Cor. 2019. Available online: https://www.apis-cor.com/dubai-project (accessed on 29 August 2023).
12. ARUP. 2018. Available online: https://www.arup.com/projects/3d-housing-05 (accessed on 29 August 2023).
13. XtreeE. 2021. Available online: http://www.xtreee.eu/ (accessed on 29 August 2023).
14. Khan S, Ilcan H, Sahmaran M, Koc M. Conceptual design of autonomous rapid mobile 3D printing system for emergency and humanitarian needs. *Mater. Today Proc.* **2022**, *70*, 1–5.
15. Khoshnevis B. Automated construction by contour crafting—related robotics and information technologies. *Autom. Constr.* **2004**, *13*, 5–19.
16. Lowke D, Dini E, Perrot A, Weger D, Gehlen C, Dillenburger B. Particle-bed 3D printing in concrete construction – Possibilities and challenges. *Cem. Concr. Res.* **2018**, *112*, 50–65.
17. Hack N, Lauer WV, Gramazio F, Kohler M, Langenberg S. Mesh-mould: robotically fabricated spatial meshes as concrete formwork and reinforcement. In *Fabricate 2014*; UCL Press: London, UK, 2017, pp 224–231.
18. BetAbram. 2019. Available online: https://betabram.com/ (accessed on 29 August 2023).
19. Maxi-Printer. 2019. Available online: https://www.constructions-3d.com/ (accessed on 29 August 2023).
20. Cybe. 2022. Available online: https://cybe.eu/ (accessed on 29 August 2023).
21. ICON. 2019, Vulcan II. Available online: https://www.iconbuild.com/ (accessed on 29 August 2023).
22. MUDBOTS. 2019. Available online: https://www.mudbots.com/ (accessed on 29 August 2023).
23. Total kustom. 2022. Available online: http://www.totalkustom.com/ (accessed on 29 August 2023).
24. WASP Crane. 2019. Available online: https://www.3dwasp.com/ (accessed on 29 August 2023).
25. Ooms T, Vantyghem G, Tao Y, Bekaert M, De Schutter G, Van Tittelboom K, et al. The Production of a Topology-Optimized 3D-Printed Concrete Bridge. In *Third RILEM International Conference on Concrete and Digital Fabrication*; Springer International Publishing: Cham, Switzerland, 2022; pp. 37–42.
26. Manju R, Deepika R, Gokulakrishnan T, Srinithi K, Mohamed MI. A research on 3d printing concrete. *Int. J. Recent Technol. Eng.* **2019**, *8*, 1691–1693.
27. Zhang J, Wang J, Dong S, Yu X, Han B. A review of the current progress and application of 3D printed concrete. *Compos. Part A Appl. Sci. Manuf.* **2019**, *125*, 105533.
28. Nodehi M, Aguayo F, Nodehi SE, Gholampour A, Ozbakkaloglu T, Gencel O. Durability properties of 3D printed concrete (3DPC). *Autom. Constr.* **2022**, *142*, 104479.
29. Khan SA, Ilcan H, Imran R, Aminipour E, Sahin O, Al Rashid A, Koc M. The impact of nozzle diameter and printing speed on geopolymer-based 3D-Printed concrete structures: Numerical modeling and experimental validation. *Results Eng.* **2024**, *21*, 101864.
30. Mata-Falcón J, Bischof P, Kaufmann W. Exploiting the Potential of Digital Fabrication for Sustainable and Economic Concrete Structures. In *Digital Concrete*; Springer International Publishing: Cham, Switzerland, 2019; pp. 157–166.
31. Matos J, Solgaard A, Santos C, Silva MS, Linneberg P, Strauss A, et al. Life Cycle Cost, As a Tool for Decision Making on Concrete Infrastructures. In *High Tech Concrete: Where Technology and Engineering Meet*; Springer International Publishing: Cham, Switzerland, 2018; pp 1832–1839.
32. Ma G, Li Y, Wang L, Zhang J, Li Z. Real-time quantification of fresh and hardened mechanical property for 3D printing material by intellectualization with piezoelectric transducers. *Constr. Build. Mater.* **2020**, *241*, 117982.

33. Kastiukas G, Ruan S, Liang S, Zhou X. Development of precast geopolymer concrete via oven and microwave radiation curing with an environmental assessment. *J. Clean Prod.* **2020**, *255*, 120290.
34. Ghaffar SH, Corker J, Fan M. Additive manufacturing technology and its implementation in construction as an eco-innovative solution. *Autom. Constr.* **2018**, *93*, 1–11.
35. Wu P, Wang J, Wang X. A critical review of the use of 3-D printing in the construction industry. *Autom. Constr.* **2016**, *68*, 21–31.
36. Siddika A, Al Mamun A, Ferdous W, Saha AK, Alyousef R. 3D-printed concrete: applications, performance, and challenges. *J. Sustain. Cem. Based Mater.* **2019**, 9, 127–164.
37. Berman B. 3-D printing: The new industrial revolution. *Bus Horiz.* **2012**, *55*, 155–162.
38. Perrot A, Rangeard D, Pierre A. Structural built-up of cement-based materials used for 3D-printing extrusion techniques. *Mater. Struct.* **2016**, *49*, 1213–1220.
39. El-Sayegh S, Romdhane L, Manjikian S. A critical review of 3D printing in construction: benefits, challenges, and risks. *Arch. Civil Mech. Eng.* **2020**, *20*, 1–25.
40. Raphael B, Senthilnathan S, Patel A, Bhat S. A review of concrete 3D printed structural members. *Front. Built Environ.* **2023**, *8*, 291.
41. Dixit MK. 3-D Printing in Building Construction: A Literature Review of Opportunities and Challenges of Reducing Life Cycle Energy and Carbon of Buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *290*, 012012.
42. Khan SA, Jassim M, Ilcan H, Sahin O, Bayer İR, Sahmaran M, et al. 3D printing of circular materials: Comparative environmental analysis of materials and construction techniques. *Case Stud. Constr. Mater.* **2023**, *18*, e02059.
43. Mir N, Khan SA, Kul A, Sahin O, Sahmaran M, Koç M. Construction and demolition waste-based geopolymers for built-environment: An environmental sustainability assessment. *Mater. Today Proc.* **2022**, *70*, 358–362.
44. Mir N, Khan SA, Kul A, Sahin O, Lachemi M, Sahmaran M, et al. Life cycle assessment of binary recycled ceramic tile and recycled brick waste-based geopolymers. *Clean. Mater.* **2022**, *5*, 100116.
45. Khan SA, Kul A, Şahin O, Şahmaran M, Al-Ghamdi SG, Koç M. Energy-environmental performance assessment and cleaner energy solutions for a novel Construction and Demolition Waste-based geopolymer binder production process. *Energy Rep.* **2022**, *8*, 14464–14475.
46. Paul SC, van Zijl GPAG, Gibson I. A review of 3D concrete printing systems and materials properties: current status and future research prospects. *Rapid Prototyp. J.* **2018**, *24*, 784–798.
47. Ma G, Wang L. A critical review of preparation design and workability measurement of concrete material for largescale 3D printing. *Front. Struct. Civil Eng.* **2018**, *12*, 382–400.
48. Perrot A, Amziane S. 3D Printing in Concrete: General Considerations and Technologies. In *3D Printing of Concrete*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2019; pp. 1–40.
49. Koç M, Khan SA, Ilcan H, Sahmaran M. Conceptual design of autonomous rapid printing system for emergency and humanitarian needs. *Mater. Today Proc.* **2022**, *70*, 1–5.
50. Khan SA, Koç M. Numerical modelling and simulation for extrusion-based 3D concrete printing: The underlying physics, potential, and challenges. *Results Mater.* **2022**, *16*, 100337.
51. 3D Systems. 2022. Available online: https://www.3dsystems.com/ (accessed on 29 August 2022).
52. Trisha Andres. Financial Times. 2013. Available online: https://www.ft.com/ (accessed on 29 August 2022).
53. 3D Priningt. 3D Printed Chair. 2019. Available online: https://3dprinting.com/ (accessed on 29 August 2022).
54. 3D Printing Industry. 2022. Available online: https://3dprintingindustry.com/ (accessed on 29 August 2022).
55. deezeen.com. 2015. Available online: https://www.dezeen.com/ (accessed on 29 August 2022).
56. bitsandsandparts.org. Puzzle Chairs. 2022. Available online: https://www.bitsandparts.org/ (accessed on 29 August 2022).
57. Goulas A, Binner JGP, Harris RA, Friel RJ. Assessing extraterrestrial regolith material simulants for in-situ resource utilisation based 3D printing. *Appl. Mater. Today* **2017**, *6*, 54–61.
58. plmdata. 2022. Available online: https://plmdata.it/ (accessed on 29 August 2022).
59. Imran R, Al Rashid A, Koç M. Material Extrusion 3D Printing (ME3DP) Process Simulations of Polymeric Porous Scaffolds for Bone Tissue Engineering. *Materials* **2023**, *16*, 2475.
60. Imran R, Al Rashid A, Koç M. Review on computational modeling for the property, process, product and performance (PPPP) characteristics of additively manufactured porous magnesium implants. *Bioprinting* **2022**, *28*, e00236.
61. Bozkurt Y, Karayel E. 3D printing technology; methods, biomedical applications, future opportunities and trends. *J. Mater. Res. Technol.* **2021**, *14*, 1430–1450.
62. Ikram H, Al Rashid A, Koç M. Additive manufacturing of smart polymeric composites: Literature review and future perspectives. *Polym. Compos.* **2022**, *43*, 6355–6380.
63. Javaid M, Haleem A, Vaishya R, Bahl S, Suman R, Vaish A. Industry 4.0 technologies and their applications in fighting COVID-19 pandemic. *Diabetes Metab. Syndr. Clin. Res. Rev.* **2020**, *14*, 419–422.
64. Nazir A, Azhar A, Nazir U, Liu YF, Qureshi WS, Chen JE, et al. The rise of 3D Printing entangled with smart computer aided design during COVID-19 era. *J. Manuf. Syst.* **2021**, *60*, 774–786.

65. Al Rashid A, Khan SA, Koç M. Product, Process, Property, and Performance (PPPP) Relationship of 3D-Printed Polymers and Polymer Composites: Numerical and Experimental Analysis. *Adv. Ind. Eng. Polym. Res.* **2023**. doi:10.1016/j.aiepr.2023.12.001.
66. Al Rashid A, Abdul Qadir S, Koç M. Microscopic analysis on dimensional capability of fused filament fabrication three-dimensional printing process. *J. Elastom. Plastics* **2021**, *54,* 385–403.
67. Khan I, Tariq M, Abas M, Shakeel M, Hira F, Al Rashid A, et al. Parametric investigation and optimisation of mechanical properties of thick tri-material based composite of PLA-PETG-ABS 3D-printed using fused filament fabrication. *Compos. Part C* **2023**, *12*, 100392.
68. Xiang DD, Wang P, Tan XP, Chandra S, Wang C, Nai ML, et al. Anisotropic microstructure and mechanical properties of additively manufactured Co–Cr–Mo alloy using selective electron beam melting for orthopedic implants. *Mater. Sci. Eng. A* **2019**, *765*, 138270.
69. Kumar KPA, Pumera M. 3D-Printing to Mitigate COVID-19 Pandemic. *Adv. Funct. Mater.* **2021**, *31*, 2100450.
70. Almulla, Haneen. "Coronavirus: Etihad Engineer Designs 3D-Printed Face Shields." The National, 24 June 2020, 1. Available online: https://www.thenationalnews.com/uae/health/coronavirus-etihad-engineer-designs-3d-printed-face-shields-1.1042959 (accessed on 29 August 2022).
71. Pinshape. 2020, Boltian Goggles. Available online: https://pinshape.com/ (accessed on 29 August 2022).
72. Metamotive Product Development. 2022. Available online: https://www.metamotiveproductdevelopment.com/ (accessed on accessed on 29 August 2022).
73. 3D Printing & 3D Scanning. 2022. Available online: https://web.iitd.ac.in/~ddz208073/Assignment_4732.html (accessed on accessed on 29 August 2022).
74. BBC News. (2020, March 16). Coronavirus: Italian 3D-printer company produces respirator valves. BBC News. Available online: https://www.bbc.com/news/technology-51911070 (accessed on 29 August 2022).
75. World Health Organization. (2021, June 25)231. Considerations for quarantine of contacts of COVID-19 cases: Interim guidance4. WHO. Available online: https://apps.who.int/iris/handle/10665/3398575 (accessed on 29 August 2022).
76. Choong YYC, Tan HW, Patel DC, Choong WT, Chen CH, Low HY, et al. The global rise of 3D printing during the COVID-19 pandemic. *Nat. Rev. Mater.* **2020**, *5*, 637–639.
77. Longhitano GA, Nunes GB, Candido G, da Silva JVL. The role of 3D printing during COVID-19 pandemic: a review. *Progr. Addit. Manuf.* **2021**, *6*, 19–37.
78. François P-M, Bonnet X, Kosior J, Adam J, Khonsari RH. 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.
79. Chatham House. (2021, February). The COVID-19 pandemic and trends in technology: Transformations in governance and society. Available online: https://www.chathamhouse.org/2021/02/covid-19-pandemic-and-trends-technology (accessed on 29 August 2022).
80. Yang G, Mo J, Kang Z, Dohrmann Y, List FA III, Green JB Jr, et al. Fully printed and integrated electrolyzer cells with additive manufacturing for high-efficiency water splitting. *Appl. Energy* **2018**, *215*, 202–210.
81. Seol M-L, Nam I, Ribeiro EL, Segel B, Lee D, Palma T, et al. All-Printed In-Plane Supercapacitors by Sequential Additive Manufacturing Process. *ACS Appl. Energy Mater.* **2020**, *3*, 4965–4973.
82. Lee H, Chidambaram Seshadri R, Han SJ, Sampath S. TiO_2−X based thermoelectric generators enabled by additive and layered manufacturing. *Appl. Energy* **2017**, *192*, 24–32.
83. Ford S, Despeisse M. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *J. Clean Prod.* **2016**, *137*, 1573–1587.
84. Ngo TD, Kashani A, Imbalzano G, Nguyen KT, Hui D. Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Compos. B Eng.* **2018**, *143*, 172–196.
85. Chung B Do, Kim S Il, Lee JS. Dynamic Supply Chain Design and Operations Plan for Connected Smart Factories with Additive Manufacturing. *Appl. Sci.* **2018**, *8*, 583.
86. Bradshaw S, Bowyer A, Haufe P. The intellectual property implications of low-cost 3D printing. *Scriptorium* **2010**, *7*, 5–31.
87. Klippstein H, Diaz De Cerio Sanchez A, Hassanin H, Zweiri Y, Seneviratne L. Fused Deposition Modeling for Unmanned Aerial Vehicles (UAVs): A Review. *Adv. Eng. Mater.* **2018**, *20*, 1700552.
88. Saboori A, Aversa A, Marchese G, Biamino S, Lombardi M, Fino P. Application of Directed Energy Deposition-Based Additive Manufacturing in Repair. *Appl. Sci.* **2019**, *9*, 3316.
89. Jeroen PJDJ, Erik DB. Innovation lessons from 3-D printing. *IEEE Eng. Manag. Rev.* **2014**, *42*, 86–94.
90. Murphy S V, Atala A. 3D bioprinting of tissues and organs. *Nat. Biotechnol.* **2014**, *32*, 773–785.
91. Yilmaz B, Al Rashid A, Ait Y, Evis Z, Koç M. Bioprinting: A review of processes, materials and applications. *Bioprinting* **2021**, *23*, e00148.
92. Ikram H, Al Rashid A, Koç M. Synthesis and characterization of hematite (α-Fe_2O_3) reinforced polylactic acid (PLA) nanocomposites for biomedical applications. *Compos. Part C Open Access* **2022**, *9*, 100331.

93. Rayna T, Striukova L. From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technol. Forecast. Soc. Change* **2016**, *102*, 214–224.
94. Verboeket V, Krikke H. The disruptive impact of additive manufacturing on supply chains: A literature study, conceptual framework and research agenda. *Comput. Ind.* **2019**, *111*, 91–107.
95. Holmström J, Partanen J, Tuomi J, Walter M. Rapid manufacturing in the spare parts supply chain. *J. Manuf. Technol. Manag.* **2010**, *21*, 687–697.
96. Delic M, Eyers DR. The effect of additive manufacturing adoption on supply chain flexibility and performance: An empirical analysis from the automotive industry. *Int. J. Prod. Econ.* **2020**, *228*, 107689.
97. Attaran M. The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing. *Bus. Horiz.* **2017**, *60*, 677–688.
98. Bogers M, Hadar R, Bilberg A. Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. *Technol. Forecast. Soc. Change* **2016**, *102*, 225–239.
99. Oettmeier K, Hofmann E. Impact of additive manufacturing technology adoption on supply chain management processes and components. *J. Manuf. Technol. Manag.* **2016**, *27*, 944–968.
100. Cui W, Yang Y, Di L, Dababneh F. Additive manufacturing-enabled supply chain: Modeling and case studies on local, integrated production-inventory-transportation structure. *Addit. Manuf.* **2021**, *48*, 102471.
101. Fawcett SE, Waller MA. Can We Stay Ahead of the Obsolescence Curve? On Inflection Points, Proactive Preemption, and the Future of Supply Chain Management. *J. Bus. Logist.* **2014**, *35*, 17–22.
102. Gress DR, Kalafsky R V. Geographies of production in 3D: Theoretical and research implications stemming from additive manufacturing. *Geoforum* **2015**, *60*, 43–52.
103. Tuck C, Hague R, Burns N. Rapid manufacturing: impact on supply chain methodologies and practice. *Int. J. Serv. Oper. Manag.* **2007**, *3*, 1–22.
104. Barz A, Buer T, Haasis H-D. Quantifying the effects of additive manufacturing on supply networks by means of a facility location-allocation model. *Logist. Res.* **2016**, *9*, 13.
105. Holmström J, Holweg M, Khajavi SH, Partanen J. The direct digital manufacturing (r)evolution: definition of a research agenda. *Oper. Manag. Res.* **2016**, *9*, 1–10.
106. Kohtala C, Hyysalo S. Anticipated environmental sustainability of personal fabrication. *J. Clean Prod.* **2015**, *99*, 333–344.
107. Laplume AO, Petersen B, Pearce JM. Global value chains from a 3D printing perspective. *J. Int. Bus. Stud.* **2016**, *47*, 595–609.
108. Chen Z. The Influence of 3D Printing on Global Container Multimodal Transport System. *Complexity* **2017**, *2017*, 7849670.
109. Dong X, Jin Y, Li T. The effect of 3D printing technology on logistics enterprises storage based on the case of UPS. *Sci. Technol. Manag. Res.* **2016**, *144*, 106–109.
110. Rogers H, Baricz N, Pawar KS. 3D printing services: classification, supply chain implications and research agenda. *Int. J. Phys. Distrib. Logist. Manag.* **2016**, *46*, 886–907.
111. Chen D, Heyer S, Ibbotson S, Salonitis K, Steingrímsson JG, Thiede S. Direct digital manufacturing: definition, evolution, and sustainability implications. *J. Clean Prod.* **2015**, *107*, 615–625.
112. Frazier WE. Metal Additive Manufacturing: A Review. *J. Mater. Eng. Perform.* **2014**, *23*, 1917–1928.
113. Chen Z. Research on the Impact of 3D Printing on the International Supply Chain. *Adv. Mater. Sci. Eng.* **2016**, *2016*, 4173873.
114. Sugiura R, Fukagawa T, Noguchi N, Ishii K, Shibata Y, Toriyama K. Field information system using an agricultural helicopter towards precision farming. In Proceedings of the 2003 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM 2003), Kobe, Japan, 20–24 July 2003; pp 1073–1078.
115. Wright S. UAVs in Community Police Work. In *Infotech@Aerospace*; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2005.
116. Siciliano B, Khatib O. Introduction. In *Springer Handbook of Robotics*; Springer, Berlin/Heidelberg, Germany, 2008; pp. 1–4.
117. López JJ, Mulero-Pázmány M. Drones for conservation in protected areas: present and future. *Drones* **2019**, *3*, 10.
118. Duan Z, Li Y, Wang J, Zhao G, Svanberg S. Aquatic environment monitoring using a drone-based fluorosensor. *Appl. Phys. B* **2019**, *125*, 108.
119. Shafiee M, Zhou Z, Mei L, Dinmohammadi F, Karama J, Flynn D. Unmanned aerial drones for inspection of offshore wind turbines: A mission-critical failure analysis. *Robotics* **2021**, *10*, 26.
120. Pieterkosky S, Ziegwied A, Cavanagh C, Thompson L. BIV meets ASV: Bio-inspired fish drones and autonomous surface vehicles for coral reef monitoring. In Proceedings of the OCEANS 2017, Anchorage, AK, USA, 18–21 September 2017.
121. Rao B, Gopi AG, Maione R. The societal impact of commercial drones. *Technol. Soc.* **2016**, *45*, 83–90.
122. Al Rashid A, Ikram H, Koç M. Additive manufacturing and mechanical performance of carbon fiber reinforced Polyamide-6 composites. *Mater. Today Proc.* **2022**, *62*, 6359–6363.
123. Ferro C, Grassi R, Seclì C, Maggiore P. Additive Manufacturing Offers New Opportunities in UAV Research. *Procedia CIRP* **2016**, *41*, 1004–1010.
124. Azarov A V, Antonov FK, Golubev MV, Khaziev AR, Ushanov SA. Composite 3D printing for the small size unmanned aerial vehicle structure. *Compos. B Eng.* **2019**, *169*, 157–163.

125. Henderson L, Glaser T, Kuester F. Towards bio-inspired structural design of a 3D printable, ballistically deployable, multi-rotor UAV. In Proceedings of the 2017 IEEE Aerospace Conference, Big Sky, MT, USA, 4–11 March 2017.
126. Barr A, Bensinger G. Google is testing delivery drone system. *Wall Street Journal* 2014.
127. Boretti A, Rosa L. Reassessing the projections of the World Water Development Report. *NPJ Clean Water* **2019**, *2*, 15.
128. Nano Sun Singapore. 2022. Available online: https://www.nanosun-main.com/ (accessed on 29 August 2022).
129. Ullah I, Rasul M. Recent Developments in Solar Thermal Desalination Technologies: A Review. *Energies* **2018**, *12*, 119.
130. Li Y, Gao T, Yang Z, Chen C, Luo W, Song J, et al. 3D-Printed, All-in-One Evaporator for High-Efficiency Solar Steam Generation under 1 Sun Illumination. *Adv. Mater.* **2017**, *29*, 1700981.
131. Salamone F, Belussi L, Danza L, Ghellere M, Meroni I. Design and Development of nEMoS, an All-in-One, Low-Cost, Web-Connected and 3D-Printed Device for Environmental Analysis. *Sensors* **2015**, *15*, 13012–13027.
132. Wang Y, Valega Mackenzie F, Ingenhut B, Boersma A. AP4.1 - Miniaturized 3D Printed Particulate Matter Sensor for Personal Monitoring. In Proceedings of the 17th International Meeting on Chemical Sensors (IMCS 2018), Vienna, Austria, 15–19 July 2018; pp. 402–403.
133. Xu X, Xiao S, Willy HJ, Xiong T, Borayek R, Chen W, et al. 3D-Printed Grids with Polymeric Photocatalytic System as Flexible Air Filter. *Appl. Catal. B* **2020**, *262*, 118307.
134. Melnikova R, Ehrmann A, Finsterbusch K. 3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials. *IOP Conf. Ser. Mater. Sci. Eng.* **2014**, *62*, 012018.
135. Richter C, Schmülling S, Ehrmann A, Finsterbusch K. FDM printing of 3D forms with embedded fibrous materials. In Proceedings of the The 2015 International Conference on Design, Manufacturing and Mechatronics (ICDMM2015), Wuhan, China, 17–18 April 2015; pp. 961–969.
136. Grimmelsmann N, Meissner H, Ehrmann A. 3D printed auxetic forms on knitted fabrics for adjustable permeability and mechanical properties. *IOP Conf. Ser. Mater. Sci. Eng.* **2016**, *137*, 012011.
137. Rural Industries Research and Development Corporation. "3D Printing." RIRDC, Aug. 2016, 1. Available online: https://agrifutures.com.au/wp-content/uploads/publications/16-034.pdf (accessed on 29 August 2023).
138. Crisostomo JLB, Dizon JRC. 3D Printing Applications in Agriculture, Food Processing, and Environmental Protection and Monitoring. *Adv. Sustain. Sci. Eng. Technol.* **2021**, *3*, 0210201.
139. Tamara Nair. 2016, 3-D Printing for Food Security: Providing the Future Nutritious Meal – Analysis Nair, Tamara. 3-D Printing for Food Security: Providing the Future Nutritious Meal. 12 RSIS Commentaries, Nanyang Technological University, 2016. Available online: https://hdl.handle.net/10356/84210 (accessed on 6 February 2024).
140. Lipton J, Arnold D, Nigl F, Lopez N, Cohen D, Norén N, et al. Multi-Material Food Printing with Complex Internal Structure Suitable for Conventional Post-Processing. Proceedings of the 21st Solid Freeform Fabrication Symposium. 2010. Available online: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=b7356b96ed47e65b19d5e2d909378fdf1e5882b7 (accessed on 29 August 2023).
141. Yang F, Zhang M, Bhandari B, Liu Y. Investigation on lemon juice gel as food material for 3D printing and optimization of printing parameters. *LWT* **2018**, *87*, 67–76.
142. Sun J, Peng Z, Zhou W, Fuh JY, Hong GS, Chiu A. A Review on 3D Printing for Customized Food Fabrication. *Procedia Manuf.* **2015**, *1*, 308–319.
143. Al Rashid A, Koç M. Additive Manufacturing for Sustainability and Circular Economy: Needs, Challenges, and Opportunities for 3D Printing of Recycled Polymeric Waste. *Mater. Today Sustain.* **2023**, *24*, 100529.