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(Review Article)

Role of 3D Printing in Agriculture and Food Industries: An Updated Review

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Abstract

3D printing, or additive manufacturing, involves creating three-dimensional objects layer by layer using various materials such as plastics, metals, and composites. In India, the application of 3D printing in agriculture has revolutionized the industry. The recent release of **Apollo 350 SLS** by Indian Institute or Science (IISC), Bengaluru, Karnataka State, India is not just a machine; it's a game-changer for India's polymer 3D printing industry. Apollo 350 SLS revolutionary 3D printer sets the stage for self-reliance and industrial transformation in India. Among the various innovations reshaping this industry, 3D printing stands out as a game-changer. 3D printing is a potential technology that can revolutionize the agriculture industry by impacting the design and performance of agricultural machinery, manufacture equipment and tools on-demand, water management, phenotyping, and pest control. 3D printing can offer cost reduction, availability, improvement, customization enhancement, and performance improvement for agricultural machinery, benefiting both farmers and consumers. On the other hand, 3D food printing also plays a beneficial role in food manufacturing. 3D food printing (3DFP) is a technology by which customized food items can be 'printed' layer by layer, as the nozzle releases the 'food ink' in a pre-programmed design. Foods can be digitally designed and physically prepared using the layer-by-layer deposition of food components, rewarding opportunities to deliver nutritionally personalized food. However, 3D printed food technology also faces challenges such as consumer acceptability, food safety and regulatory concerns. Possible adverse health effects due to over consumption or the ultra-processed nature of 3D printed foods are major potential pitfalls.

Keywords: Additive manufacturing Agriculture; Computer-aided-design (CAD); Food printing; Farming equipment; FarmShelf; 3D Printing; India; 3DFP (3D food printing)

1. Introduction

3D printing, also known as additive manufacturing (AM), is a technology that creates objects by depositing layers of material on top of each other [1-92-118]. 3D printing has been widely used in various industries, such as agriculture, food industries, aerospace, automotive, medical (Organ printing, surgical planning, medical education and training, medical research, anatomic prosthesis, drug delivery), and building construction including 3D hempcrete blocks [1-92,

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118, 119]. 3D printing, is also known as additive manufacturing, is a method of creating a three dimensional object layer-by-layer using a computer created design (CAD) [1-70]. 3D printing or additive manufacturing is a process of making three dimensional objects from a digital file [1-92]. The creation of a 3D printed object is achieved using additive processes. In an additive process, an object is created by laying down successive layers of material until the object is created [1-70]. Each of these layers can be seen as a thinly sliced cross-section of the object [1-92]. There is one exception though, and it's called volumetric 3D printing. The American Society for Testing and Materials (ASTM) International Committee F42 has adopted the term additive manufacturing (AM) for techniques that produce physical objects from three-dimensional (3D) digital data [3]. Additive manufacturing is a great asset for many different industries and can be used for various applications, but agriculture is one of the industries starting to make the most of the cutting-edge technology that is 3D printing [1-92]. Additive manufacturing has taken hold in the automotive and transportation sectors, and similar uses have been seen in the manufacture of agricultural machinery [1-92]. For example, in 2022, renowned manufacturer John Deere produced over 4,000 parts using additive manufacturing in one year. This was its first step in implementing additive manufacturing at its specialized center in Mannheim, Germany [1-92]. Agricultural research has evolved significantly in recent years, driven by technological advances that are redefining traditional practices. Among these innovations, 3D printing is emerging as a revolutionary tool that could help to redefine modern agriculture [1-95]. The convergence of 3D printing and agriculture promises to mark a new era in the way agricultural resources are grown and managed.

Commonly, 3D printers feed on plastic, but with the recent advancement, now they can print metals, ceramics, and food [116]. The benefits of using 3D printing, in general, are flexibility in design, the accuracy of the product, minimum waste, material customization, and less human interaction [116]. In general, the 3D printing method is adding layer by layer of materials in predetermined routes generated by g-code[116]. To get the g-code, a slicer software will "slice" 3D model into 2D layers and generate the construction pattern needed to print the model[116].

Another area is food processing where 3D food printing (3DFP) is a technology by which customised food items can be 'printed' layer by layer, as the nozzle releases the 'food ink' in a pre-programmed design [1-94-111-121]. Foods can be digitally designed and physically prepared using the layer-by-layer deposition of food components; unleashing opportunities to deliver nutritionally personalized food and new food-human interactions [93-95-111]. Although several food printing technologies are now available, the most common 3D food printing (3DFP) method is based on a controlled layer-by-layer deposition of a food ink by cold or hot extrusion followed eventually by a final post-treatment [93, 94, 95-111]. Personalized 3D food printing (3DFP) refers to special dietary necessities and can be promising to prevent different non-communicable diseases through improved functional food products, containing bioactive compounds like proteins, antioxidants, phytonutrients, and/or probiotic [93-95-111-121]. In food production, 3D printing is used both in manufacturing of mechanical parts, e.g. nozzles for extruders , and the actual production of food and creation of dishes by so-called 3D food printing (3DFP) [93, 94, 95-113-121].

Nowadays, 3D printing technology is used in multiple industries such as agriculture, food, architecture and construction, aerospace and automotive, the energy industry, and medical industry. Three-dimensional printing technology has also shown its potential for applications in the food and nutrition context [1-113, 118]. Because of its digital design, accurate quality control, environmentally friendly, energy-efficient, and low-cost characteristics, 3D food printing plays a beneficial role in food manufacturing [1-113]. 3D printing of food materials is among the innovations that could revolutionize people's food choices and consumption [1-113, 116]. Food innovation and production have advanced considerably in recent years and its market has shown rapid annual expansion [116]. Printing food technologies are considered as a potential solution for producing customized foods such as military food, and astronaut food [1-113, 116]. The advantages of using 3D food printing in manufacturing include customizing the shape and content of food, enhancing the utilization of ingredients, and creating food that meets personalized nutritional needs [1-113]. In food 3D printing, instead of non-edible materials, the filament uses a formalized food ink, the ink is inserted into the extruder. To print the food, the extruder forces the ink, either viscous or watery, into the nozzle [116]. The actuators will move the nozzle in each direction to create the specific paths [116]. Important parameters required for successful printing include but not limited to temperature, extrusion rate, nozzle height, diameter of the nozzle, extruder moving speed, and slicer software [116]. After the food has been printed, sometimes for certain types of food a post-processing (baking, frying, toasting, steaming, etc.) is necessary [116].

During the few years, cake, which consists of starch, sugar, corn syrup, yeast, and cake frosting, chocolate, cheese, mashed potato, dough, ice cream, peanut butter, and blends of fruits and vegetables have been successfully printed [1-113, 116]. Some researchers have begun to look for unusual food ink such as insects, algae, bacteria, and fungi [116]. Today, chicken, turkey, fish surimi, scallop, shrimp, and even beef have also been printed [1-113, 116]. The critical variables for all types of food to be printed lies on its rheological and physical properties [116]. Since many foods have unprintable properties, some additives/flow enhancers are added to the food [1-113, 116]. By altering its properties, the foods printability has been improved [116].

Current applications include chocolate, meat and meat alternatives [11,12], egg white protein objects, and fruit and vegetable smoothies [1-113]. Several restaurants have used 3D food printers to provide customers with visually appealing food and unique dining experiences [1-113-121]. Three-dimensional printed food is also used to support sustainability. For instance, unshaped fruits and vegetables or insect proteins were used to create 3D printed food for reducing food waste and CO_2 emissions from livestock [1-113]. 3D printing is no longer limited to small prototypes or niche parts. In 2025, advancements in large-format 3D printing will unlock new opportunities for industrial-scale applications, especially in food, agriculture, construction, automotive, and energy sectors. Looking ahead over the next 5 to 10 years, the 3D printing industry is expected to make substantial strides [1-113-121]. Additive manufacturing (AM) will become a major enabling production technology across more than ten industries [1-113]. This will range from on-demand spare parts production to large-scale serial applications[1-113-121]. In the following section, the applications of 3D in agriculture sector and food industries has been discussed.

2. Role of 3D Printing in India

Although countries like the US, Canada, UK, Japan, France, Australia, Germany, and China have extensively adopted additive manufacturing (AM), India has been slower to do so [1, 11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64, 119, 120, 121]. The potential of additive manufacturing (AM), to propel socio-economic growth has caught the attention of the Indian manufacturing ecosystem. The first instances of additive manufacturing (AM), in India can be traced back to the late 1990s when global industries started exploring rapid prototyping. During this period, a few Indian companies and educational institutions began importing 3D printers, primarily for research and prototyping [1, 11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64, 119, 120-121]. The Indian Institute of Technology (IIT) Mumbai, Maharashtra state, India was among the pioneers, setting up an additive manufacturing (AM) lab to explore the potential of this novel technology. By the mid-2000s, India has seen the emergence of its first domestic 3D printer manufacturers [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. Firms like Divide By-Zero and Altem Technologies began offering indigenously developed 3D printers, challenging the market dominance of imported machines. These machines, primarily employing fused deposition modeling (FDM), catered to the growing demand from educational institutions and small-scale industries [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The 2010s marked a significant turn in India's additive manufacturing (AM) journey. The country witnessed a surge in start-ups dedicated to 3D printing, offering services ranging from prototyping to finished product manufacturing. Companies like Imaginarium, Think3D, and Sahas_Softech made notable strides in the industry. This period also witnessed the emergence of metal 3D printing in sectors such as aerospace, healthcare, and automotive [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The Government of India, recognizing the potential of additive manufacturing (AM), launched initiatives under the 'Make in India' campaign to promote indigenous manufacturing and R&D in 3D printing[11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The establishment of the Centre of Excellence in Additive Manufacturing (CoE-AM) at IIT Hyderabad, Telangana state, India in 2017, in collaboration with Applied Research International, was a significant step in this direction. The most recent years marked a key shift in India's additive manufacturing (AM) journey [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The decade witnessed the rapid adoption of 3D printing across various industries, propelled by technological advancements, decreasing costs, and a growing comprehension of additive manufacturing (AM) potential. The Ministry of Electronics and Information Technology (MEIT), Government of India, being a nodal agency for Digital Technology, has evolved a strategy to promote all the verticals of the additive manufacturing (AM) sector, including machines, materials, software, and designs to leverage the untapped business opportunities in this emerging technology that will unfold in the near future. India's National Strategy for Additive Manufacturing is geared towards building a resilient ecosystem that attracts global additive manufacturing (AM) expertise and fosters local adoption. This aligns with the 'Make in India' and 'AtmaNirbhar Bharat Abhiyan' initiatives, seeking self-reliance through 3D printing [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The primary focus is on enhancing domestic production, reducing imports, and promoting innovation. To achieve these goals, India is investing in advanced additive manufacturing (AM) technologies, ensuring the economic stability of its 3D printing sector, and aimed for technological [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The National Strategy aspires for India to carve out a 5% stake in the global additive manufacturing (AM) market, with the aim of contributing nearly US$ 1 billion to the GDP by 2025. The targets encompass: Fostering 100 innovative start-ups in additive manufacturing (AM) and developing 50 Indian-centric AM technologies. Another aim is to positioning India as a prime hub for 3D printed design and manufacturing [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. Amplifying additive manufacturing (AM) awareness across 500 diverse sectors, AM Landscape in India and Government of India has started Initiatives such as 3D Printing Lab. The National Institute of Electronics & Information Technology, Aurangabad, has established a 3D printing lab and offers certification courses in 3D printing. Atal Innovation Mission: Under this mission, Atal Tinkering Labs have been set up and equipped with modern technologies, including 3D printers and students are encouraged to innovate using these resources [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. MoU with US Institute: The

Gujarat government has partnered with the US Institute of 3D Technology (USI3DT) and 3D systems to create seven 3D printing Centers of Excellence in engineering colleges nationwide. 3D Bioprinting Lab: A collaboration between Andhra Pradesh MedTech Zone and the University of Wollongong has led to establishment of a 3D Bioprinting Lab. The National Centre for Additive Manufacturing (NCAM) has been established by the Ministry of Electronics and Information Technology (MeitY) in partnership with the Government of Telangana and industry [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. NCAM aims to create a sustainable ecosystem for product innovation, established a comprehensive ecosystem for additive manufacturing (AM) adoption in industries, facilitate cutting-edge technologies, guide policy improvements, empower major firms in AM adoption, foster innovation and promote skill training activities to generate a talented workforce. [1, 11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64].

Very recently in 2025, The Indian Institute of Science's (IISc), Foundation for Science, Innovation and Development (FSID), Bangaluru, Karnataka state, India unveiled what it claims is India's first domestically developed Selective Laser Sintering (SLS) 3D printer — the Apollo 350 SLS [114, 115]. Marking a significant milestone in India's additive manufacturing journey, the Apollo 350 SLS, India's first Polymer Selective Laser Sintering (SLS) 3D printer, was launched by Shri H.D. Kumaraswamy, Union Minister for Heavy Industries and Steel, Government of India, New Delhi, at IMTEX 2025, India's largest machine tool expo [114, 115]. By providing affordable, high-performance, and versatile solutions, the Apollo 350 SLS opens new possibilities for Indian manufacturers in sectors like automotive, aerospace, healthcare, and consumer goods[114, 115]. The Apollo 350 SLS is not just a machine; it's a game-changer for India's polymer 3D printing industry. Launching the Apollo 350 SLS solidifies India's position in the global additive manufacturing landscape[114, 115]. The initiative aligns with the government's vision of "Make in India" by fostering innovation, reducing costs, and advancing the domestic manufacturing ecosystem. The Apollo 350 SLS is not just an achievement for the country's additive manufacturing sector but a testament to India's technological potential and collaborative innovation[114, 115]. As it takes center stage at IMTEX 2025, this revolutionary 3D printer sets the stage for self-reliance and industrial transformation in India[114, 115].

Private Sector Initiatives: INTECH Additive Solutions: Based in Bengaluru, Karnataka, India, INTECH is a leader in metal 3D printing in India. They have developed software for additive manufacturing (AM), designed India's first metal printer, and launched a digital academy for additive manufacturing (AM) training [1, 11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. Ace Micromatic Group: Their AMACE Solutions wing unveiled their latest large-format laser powder bed fusion machine, the ALM- 400, at IMTEX 2023. Wipro: The company introduced 'Addwize,' a program aimed at helping organizations adopt and scale metal additive manufacturing (AM) use for business advantages [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. AM Chronicle: AM Chronicle is a renowned information and content platform for the additive manufacturing (AM) industry in India. AM Chronicle is the media vertical of the Indian 3D Printing Network. 3) Collaborative Efforts: COE at IISc Bengaluru: The Department of Heavy Industries collaborated with Wipro to create India's first industrial-grade 3D printer [1, 11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. HP Inc: An MoU was signed with the Andhra Pradesh government to build a 3D printing Centre of Excellence. Stratasys and NTTF: They have launched India's first AM certification course to bridge industry skill gaps [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 4) Academia and Research: Various esteemed institutions in India are currently utilizing AM technology, including: 1) International Advanced Research Centre (ARC), Hyderabad (techniques: SLM, OED). 2) Defence Metallurgical Research Laboratory (DMRL) (technique: LENS). 3) Raja Ramana Centre for Advanced Technology (RRCAT), Indore (technique: LENS). 4) Central Mechanical Engineering Research Institute (CMERI), Durgapur. 5) Central Glass and Ceramic Research Institute (CGCRI), Kolkata (technique: SLM). 6) Central Electrochemical Research Centre (CECRI), Karaikudi. 7) Central Manufacturing Technology Institute (CMTI), Bengaluru (techniques: SLM, OED). 8) Indian Institute of Technology, Mumbai (IITB) (techniques: wire-LAM, CMTJ). 9) Indian Institute of Technology, Hyderabad (IITH) (technique: Wire ARC). 10) IIT Kharagpur (technique: SLM) [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64].

3. 3D printing Applications in India

Investment in 3D printing technologies has also been marked. Most especially from the Government of India who in 2022 adopted the National Strategy on Additive Manufacturing. In this strategy, the mission is to position India as a global innovation and research hub for AM [1, 11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The Ministry of Electronics and Information Technology (MeitY) increased India's share in global additive manufacturing to 5% by 2025. Furthermore, the country has achieved targets such as the creation of 50 Indian-specific technologies for materials, machines and software, 100 new AM startups, 500 new products and produced new jobs for skilled workers who have been trained in 3D printing [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. However, 3D printer manufacturers do not make up the majority of the 3D printing business in India and honour goes to service bureaus. There are a number of notable players in India including Imaginarium, Rapid 3D, Think3D, Wirpro3D and Vektor3D Systems, among many others established 3D printing business [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. This of course means that these bureaus are incredibly important in the country and are key to helping drive adoption of AM, and by the Government of

India supported them [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The relevance and importance of 3D printing service bureaus still remains high in India, a country where people would usually prefer to ‘try first and then buy [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. Also, the pace at which new 3D printing technologies are introduced for commercial use also makes a compelling case for OEM’s and part manufacturers to collaborate with service bureaus [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. Following are the few growing sectors of business where 3D printing technology has been adopted.

1) Electronics: The electronics sector, a high-volume manufacturing domain, grapples with challenges, causing a disability rate of 8.5-11%. Despite its potential, the adoption rate of AM in electronics remains sluggish [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. AM techniques in this sector usually deploy material jetting solidified by ultraviolet light using conductive and insulating inks. The Ministry of Electronics and Information Technology has launched initiatives to bolster the domestic electronics landscape. 2) Aerospace: The Aerospace sector in India is dominated by imports; about 70% of raw materials, including special alloys, and more than 50% of electronic components in satellites [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The country’s defense MRO market is predicted to hit $2.5 billion by 2025. 3) Defense: India stands as the world’s second-largest defense equipment importer. Annually, the defense procurement orders touch an astounding $100 billion [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. Recent FDI norms have been revamped to permit up to 74% foreign investment in the defense sector [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 4) Automotive: India’s automotive industry, contributing 7.5% to the national GDP, witnessed imports of auto components worth $17.6 billion in 2018-19. As the industry transitions to BS-VI norms, AM technologies present promising benefits. A notable instance includes a premier auto manufacturer in India leveraging Stratasys’ AM technology to save significantly in manufacturing costs. 5) Medical Devices: A majority of India’s medical device requirements, between 70-90%, are fulfilled through imports [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The sector is poised for growth, with projections estimating it to be worth $25-30 billion by 2025. The nation saw a staggering 4,67,044 road accidents in 2018, underscoring medical device needs. Notably, 3D-printed prosthetic limbs are emerging as a cost-effective solution in India. 6) Construction and Architecture: Recent data from March 2020 reveals cost overruns in 403 infrastructure projects, each exceeding Rs 150 crore. AM has been instrumental in various construction endeavours, from housing to bridge fabrication. A groundbreaking innovation from IIT Madras and a local startup has introduced a technology enabling concrete to solidify in a mere 3-5 hours [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 7) Aerospace and Defense: HAL’s Foray into 3D Printing: Hindustan Aeronautics Limited (HAL) partnered with Wipro 3D to develop a 3D-printed aircraft component, marking a significant milestone in India’s aerospace sector. The first fully 3D printed Rocket Engine: Indian space startup Agnikul Cosmos has successfully tested the world’s first fully 3D-printed rocket engine in 2022, with support from the Indian National Space Promotion and Authorization Center (IN-SPACe) and the Indian Space Research Organization (ISRO) [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The test validated the technological possibility of creating rocket engines as a single piece of hardware. 8) Healthcare and Biomedical: Customized Implants and Surgical Guides: Osteo3D, based in Bangalore, has led 3D printing medical models and surgical guides, assisting surgeons in planning complex procedures, especially in maxillofacial surgeries. Bioprinting Innovations: IIT Delhi’s research in 3D bioprinting of tissues resulted in the development of a bioprinted cartilage, heralding a significant advancement in regenerative medicine[11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 9) Automotive: Rapid Prototyping at Mahindra: The Mahindra Group has integrated AM into its design process, streamlining prototype development. On-Demand Spare Parts by Tata Motors: Embracing AM for producing spare parts has allowed Tata Motors to reduce inventory costs and improve parts availability [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 10) Construction: India’s first 3D Printed Security Pavilion: Godrej Construction and IIT Madras start-up, Tvasta, have jointly created India’s first 3D Printed Security Pavilion at the Godrej & Boyce Campus in Mumbai. Using a Robotic Arm 3D Printer, the innovative structure demonstrates the future potential of 3D printing in construction [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 11) World’s first 3D printed temple: Apsuja Infratech and Simpliforge Creations are constructing the world’s first 3D printed temple in Siddipet, Telangana [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. This innovative 3,800 sq. ft temple, showcasing unique Hindu deity designs, highlights the vast potential of 3D printing in architecture [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. The construction was executed with Simpliforge’s advanced robotic arm system and indigenous materials, 12) Kerala’s Debut 3D Printed Building: ‘Amaze 28’, Kerala’s first 3D printed building at PTP Nagar KESNIK campus, was constructed in 28 days and cost Rs 11 lakh. Using Tvasta’s software, this efficient construction method promises faster and more cost-effective building processes. The technology significantly reduces labour and time, potentially shifting traditional construction techniques [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64].

4. Role of 3D printing in Agriculture

In India, the application of 3D printing in agriculture and its potential has revolutionized the industry [1-95]. The agricultural sector, a cornerstone of India’s economy, is witnessing a technological revolution. Among the various innovations reshaping this industry, 3D printing stands out as a game-changer [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 3D printing is a potential technology that can revolutionize the agriculture industry by impacting the design and performance of agricultural machinery [1-95]. 3D printing can offer cost reduction, availability, improvement, customization enhancement, and performance improvement for agricultural machinery, benefiting both farmers and consumers [1-90]. From manufacturing customized farming equipment to advancing precision agriculture, 3D printing is paving the way for a more efficient and sustainable future in farming [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. One of the most significant impacts of 3D printing in agriculture is the ability to manufacture equipment and tools on-demand [1-95]. This trend is particularly beneficial for farmers who need customized implements suited to their specific needs [1-95]. Farmers can design and print tools like nozzles for irrigation systems or seed planters tailored for specific crops, enhancing efficiency and productivity[1-95]. 3D printing enables rapid prototyping, allowing farmers and manufacturers to quickly test and refine new designs of cost effective prototyping[11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. In remote areas, farmers can print essential tools and spare parts on-site, reducing downtime and reliance on distant suppliers[1-95].

3D printing also has potential applications in the agriculture sector, especially in the design and performance of agricultural machinery [1-95]. Agricultural machinery is essential for modern farming, as it helps farmers to perform various tasks, such as plowing, seeding, harvesting, and processing [1-95]. However, agricultural machinery also faces several challenges, such as high cost, low availability, lack of customization, and environmental impact [1-95]. 3D printing can reduce the cost of agricultural machinery by eliminating the need for expensive molds, tools, and assembly[1-95]. 3D printing can also enable the production of spare parts on-demand, reducing the inventory and transportation costs [1-95]. Furthermore, 3D printing can use less material and energy than conventional manufacturing, and lowering the environmental cost [1-95]. 3D printing can improve the availability of agricultural machinery by enabling local and distributed production [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 3D printing can allow farmers to produce their own machinery or parts, or access them from nearby service providers, reducing the dependence on distant suppliers [1-95]. Moreover, 3D printing can enable the rapid prototyping and testing of new designs, accelerating the innovation cycle [1-95]. 3D printing can enhance the customization of agricultural machinery by allowing the creation of complex and unique shapes, structures, and functions [1-95]. 3D printing can enable farmers to design and produce machinery or parts that suit their specific needs, preferences, and conditions [1-95]. For example, 3D printing can enable the fabrication of customized tools, sensors, irrigation systems, and vertical farming components[1-95]. Furthermore, 3D printing can improve the performance of agricultural machinery by enabling the use of novel and advanced materials, such as biodegradable, bioactive, bio-mimetic, and bio-inspired materials [1-95]. 3D printing can also enable the integration of multiple functions and features, such as electrical, mechanical, thermal, and optical properties, into a single part [1-95]. For instance, 3D printing can enable the production of edible and functional foods, microbial and enzymatic bioreactors, and water desalination devices [1-95].

Farming equipment is massive, complex, and expensive. As a result, replacing a part can quickly become expensive; especially if the machine is outdated and replacement parts are no longer available, or difficult to find [1-95]. By utilizing 3D printing solutions, these replacement parts can be produced quickly to decrease down time, which is important as agricultural applications are often time dependent due to variations of the weather and how the crops need to be processed to keep the fields on a schedule[1-95]. These machineries are also vital components in food production from tractors and harvesters to seeders and fertilizer spreaders[11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. By increasing cost savings and productivity while decreasing lead times, 3D printing in agriculture solutions innovate multiple aspects of the industry[1-95]. Most of the time, farmers are working with specialized machines[1-95]. These are massive and expensive machines. Even to replace just one part, it can be quite expensive[1-95]. Or the part that the farmer is searching for is maybe not on the market anymore. In this case, additive manufacturing is an amazing solution. Just like for the automotive industry, it is possible to print spare parts for farming machines. That is exactly the project of GVL Proto Poly [1-95]. They are actually receiving a lot of 3D printing demands from farmers looking for new parts for their machines [1-95].

Farming has come a long way with new technologies over the past few decades[1-95]. One of the developments is 3D printing, which could change how farmers make and use their equipment[1-95]. With 3D printing, farmers can create custom tools and machines whenever they need them, making farming more efficient, cost-effective, and sustainable[11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. According to a report by Markets and Markets, the 3D printing market in agriculture is projected to reach USD 4.8 billion by 2025, growing at a CAGR of 22.3% from 2020 to 2025 [1-95]. 3D printing technology plays a major role in agriculture as it simplifies processes including food production, transportation, and marketing [1-95]. As a result, 3D printing applications are on the rise across the industry to optimize the existing workflows[1-95]. Currently farmers have seen enhancements in structural operations, replacement parts on the equipment, day-to-day tools and fixtures needed by the farmers [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64]. 3D Printed tools are regularly used to plant crops as they can improved the process exponentially by increasing efficiency and customizations[1-95]. These tools are produced quickly, efficiently, and remotely to offer benefits from all sides, including energy and money savings [11, 12, 25-40, 47-49, 51, 52, 54, 58, 60-64].

While the agricultural sector has already witnessed the diverse applications made possible through 3D printing, it is poised to undergo significant evolution in the future[1-95]. This technology holds tremendous potential, offering an array of advantages to agriculture, spanning from customized tools to intricate devices[1-95]. The continued integration of 3D printers into agriculture is imperative, as the technology's utility is yet to be fully realized.[1-95]. As we peer into the future, the 3D printing industry still has much to contribute to agriculture, promising to become an increasingly commonplace presence[1-95]. This advancement is exemplified by the growing convergence of 3D printing and recycling, where the technology serves as a valuable solution for repurposing discarded plastic or metal materials found on farms[1-95]. These materials, hitherto overlooked, can be transformed into new tools and many other practical 3D-printed devices, enhancing sustainability and resourcefulness in agriculture [1-95].

Precision agriculture aims to optimize farming practices through detailed monitoring and control [1-95]. 3D printing is contributing significantly to this field by enabling the production of advanced sensors and devices[1-95]. 3D printed sensors can monitor soil moisture, nutrient levels, and crop health, facilitating precise and efficient farming interventions [1-95]. Components for agricultural drones and robots can be 3D printed, supporting activities like planting, monitoring, and harvesting with greater precision and less labour[1-95]. Sustainability is a growing concern in agriculture, and 3D printing is offering eco-friendly solutions that align with this need. The use of biodegradable materials in 3D printing is on the rise, creating compostable planting pots, eco-friendly packaging, and sustainable waste management tools[1-95]. 3D printing produces less material waste compared to traditional manufacturing methods, contributing to a more sustainable agricultural production [1-95].

The agricultural industry is also exploring advanced bioengineering through 3D printing, with exciting developments on the horizon [1-95]. In another development researchers are working on bio-printing plant cells and tissues, which could revolutionize how crops are grown and studied, potentially leading to more resilient plant varieties[1-95]. In livestock farming, 3D bioprinting is being used to produce **cultured meat**, offering a sustainable alternative to traditional meat production with reduced environmental impact[1-95]. Efficient water management is critical in agriculture, and 3D printing is playing a key role in developing innovative irrigation solutions [1-95]. Farmers are leveraging 3D printing to create customized irrigation components that optimize water usage and enhance crop yields [1-95]. 3D printed sensors and control systems are being used to monitor and manage water resources effectively, ensuring optimal irrigation and reducing waste [1-95]. The synergy between 3D printing and smart farming technologies is unlocking new possibilities for agriculture[1-95]**.** Synergy: Combining IoT [96-100] with 3D printed devices enhances smart farming practices. For example, sensors and actuators can be connected to IoT systems for real-time data collection and automated decision-making [1-95]. AI algorithms[96-98] can optimize the design and functionality of 3D printed farming tools, leading to smarter and more adaptive agricultural practices [1-95].

Pest control is a significant challenge in agriculture, and 3D printing is emerging as a valuable tool in natural pest management and the development of systems for producing sterile insects[1-95]. 3D Printed Pest Control Devices: Innovative 3D printed traps and devices are being designed to control pest populations without harmful chemicals. These devices can be customized to target specific pests effectively[1-95]. Production of Sterile Flies: 3D printing is facilitating the development of systems for the Sterile Insect Technique (SIT), a method used to control pest populations by releasing sterile males into the wild. This technique reduces the need for chemical pesticides and is environmentally friendly [1-95]. 3D printing is undeniably transforming the agricultural sector [1-95]. From manufacturing customized tools to fostering sustainable practices, enabling precision farming, and offering innovative pest control solutions, the potential applications of 3D printing are vast and continuously expanding[1-95]. As we look to the future, the integration of 3D printing in agriculture promises to drive innovation, enhance efficiency, and contribute to a more sustainable and prosperous farming landscape [1-95]. Furthermore, IIT Madras [28], Tamilnadu, India has opened a state-of-the-art additive manufacturing lab featuring a 3D printing farm equipped with over 25 FabMachines printers from Fabheads Automation[1-95]. The initiative marks a significant milestone in advancing additive manufacturing education and innovation in India[28]. The collaboration between IIT Madras [28] and Fabheads highlights the growing importance of home grown talent and technology in advanced manufacturing[1-95]. The integration of FabMachines technology [28] aims to provide students with practical experience in advanced manufacturing processes, enhancing their skills and understanding [1-95].

Additive manufacturing technology can also be leveraged to develop customized irrigation systems, leading to better water management in agriculture [1-95]. It also ensures an efficient and environmentally responsible approach to cope with frequent irrigation difficulties [1-95]. Making water available to every plant is a significant problem to overcome, as irrigation is a critical component of agricultural success[1-95]. Installing a reliable irrigation system can be a huge headache for farmers since it is costly and time-consuming as the pipes must be brought from a supplier to the agricultural field, giving little flexibility or scope for how changes in the landscape will affect the irrigation pattern [1-95]. Furthermore, more than 60% of water is lost owing to leaks or evaporation. To address these difficulties, companies are using 3D printers to create polymer pipes on farmland that form a honeycomb structure and allowed water to seep out, much like a sponge [1-95]. These pipes take moisture from the soil and transmit it to the plants, simplifying the whole process of seed planting for farmers [1-95]. Therefore, additive manufacturing technology is ensuring an efficient and eco-friendly way to deal with common irrigation problems [1-95].

Phenotyping in agriculture is the process of observing and analyzing plants to make predictions about their condition in a given space[1-95]. More specifically, phenotyping is the result of the interaction between a plants genetic information and its environment, and provides a better understanding of its growth, development and reaction to environmental conditions [1-95]. A study published in 2024 set a milestone in the use of additive manufacturing for plant phenotyping. A collaboration between the Institute for Sugar Beet Research (IFZ) and the University of Bonn resulted in a 3D-printed plant model for accurate and reliable phenotyping [1-95]. To provide a reference tool during the data collection and parameter extraction process, the scientists developed a 3D-printed sugar beet plant model using FDM technology [1-95]. This innovative study was carried out by an IFZ doctoral student. Jonas Bömer emphasized the importance of this model: "3D printing enabled us to create a cost-effective reference tool to guarantee the integrity of the data collected [1-95].

This research also made extensive use of 3D scanning for data collection. Indeed, 3D scanning makes it possible to create high-resolution digital models of crops, making it easier to monitor their growth and development, and to detect potential problems in good time. Jonas Bömer reported that by analyzing the soil, farmers can improve soil management and implement measures to prevent erosion. The interaction of robots with crops is another problem that can be solved by interpreting depth information. One example is fruit harvesting in automated greenhouses, which reduces and simplifies labour-intensive harvesting tasks [1-95].

Thermoplastics are widely used in agriculture. However, the waste they generate has a direct impact on soil health and affects biodiversity. To remedy these problems, solutions such as the "6R model" (reject, redesign, reduce, reuse, recycle and recover) proposed by the United Nations are being employed, and farmers are increasingly encouraged to use natural or biodegradable alternatives. Recent studies have found alternatives in materials with different properties. For example, a publication dating from 2021 proposes 4D printing as the main process for creating materials useful for agriculture. This study is entitled 4D Printing: Prospects for the production of sustainable plastics for agriculture, and is the result of collaboration between the University of Patras, the Agricultural University of Greece and the Italian Institute of Technology in Genoa[1-95].

4D printing is an evolution of 3D printing that adds the dimension of time. In this case, printed objects are made from intelligent materials that can change their shape or properties in response to external stimuli, such as heat, light, water or movement[1-95]. While 4D printing is mainly used in fields such as medicine, applications in agriculture are minor or non-existent [1-95]. The team's research showed that if 4D printing were applied to agriculture, it would be possible to increase the biodegradability, environmental, economic and production benefits of plastics in agriculture [1-95]. But the main obstacle to wider use is the novelty of the 4D printing process[1-95]. Another example of the use of additive manufacturing for soil research can be found in a 2021 publication by a multidisciplinary team from the University of Virginia in the USA. This study reported the 3D printing of biologically active soil structures, and analyzes the possibilities of 3D printing soil structures in which seeds would germinate [1-95].

Irrigation systems can be improved by designing specific components for 3D printing[1-95]. Nozzles and connectors, for example, optimize water distribution and reduce waste. Starting with insect traps, additive manufacturing makes it possible to design and manufacture specific traps for different types of pest[1-95]. These traps can be optimized to attract and capture insects. Next, we can find applications in pheromone-releasing devices, which are chemicals designed to attract or repel insects. They can be created by 3D printing and designed for controlled dispersion[1-95]. Another application for additive manufacturing is the production of horizontal crops for small spaces[1-95]. Italian company Hexagro is a specialist in this application. It uses 3D printing processes to create modular, customizable structures that can be adapted to the specific needs of each space and type of crop[1-95]. This includes the manufacture of trays, supports, irrigation channels with designs optimized for plant growth, efficient water and nutrient management[1-95]. The ability to rapidly produce customized components significantly reduces development costs and lead times, enabling Hexagro to continually innovate and improve its growing systems[1-95]. The projects mentioned the applications, the benefits identified and the results confirmed that 3D printing has development potential in agriculture[1-95]. To some extent, this technology is still in its infancy in the agricultural sector[1-95].

3D printing in agriculture offers practical solutions for creating custom equipment and tools tailored to farmers' specific needs [1-95]. For **Planting**, farmers can print custom seed planters and precision seed drills to enhance planting accuracy and efficiency. In **Irrigation**, they can design specialised sprinkler heads and drip irrigation components to optimise water usage [1-95]. **Harvesting** becomes more efficient with specialised harvesting blades and adjustable baskets designed for different crops [1-95]. **Monitoring** tools, such as soil moisture sensors and crop health monitors, helped to manage irrigation and detection of early issues [1-95]. Additionally, 3D printing allows for the quick production of replacement parts for machinery and custom tool handles, reducing downtime and maintenance costs [1-95]. In **Animal husbandry**, farmers can print custom livestock tags and feeding equipment suited to various livestock types [1-95]. Several innovative startups are combining the power of 3D printing with the Internet of Things (IoT) to bring cutting-edge solutions to the agricultural sector[1-95]. Here are some examples; **FarmBot:** FarmBot, an open-source company, uses 3D printing to create customisable farming equipment. The FarmBot system, controlled via IoT, automates planting, watering, and monitoring crops. This integration allows farmers to optimize their farming practices and increase yields while reducing labor costs. (*Location: USA)* [1-95]. **Prospera Technologies:** Prospera Technologies combines 3D printing with IoT and developed advanced monitoring systems for farms [1-95]. Their 3D-printed sensors and cameras gather data on crop health, soil conditions, and weather patterns [1-95]. This data is then analysed to provide farmers with actionable insights, helping them make informed decisions to enhance productivity (Location: Israel) [1-95]. Dr. Joshua Pearce, affiliated with Michigan Technological University, has conducted an extensive study exploring the potential of open-source 3D printing to benefit small-scale farms in developing countries[1-95]. Remarkably, a significant portion of the world's organically managed land is situated within these regions, yet farmers often contend with labour-intensive tools [1-95]. Additive manufacturing provides a transformative solution, enabling the production of more efficient, locally adapted tools[1-95]. This innovative approach not only holds promise for enhancing organic farming practices but also extends its benefits to animal husbandry and water management in these agricultural communities [1-95]. By leveraging additive manufacturing, Farmshelf efficiently customizes components essential for their project, including mounting brackets and plant hangers [1-95]. 3D printing expedites the creation of tailor-made parts, allowing for swift prototyping and testing[1-95]. In contrast, employing traditional manufacturing methods such as injection molding would not only be more time-consuming but also significantly more expensive [1-95]. In an exciting development, Italian start-up Hexagro Urban Farming is at the forefront of innovation in urban farming and vertical gardens [1-95]. Their project, the "Living Farming Tree," incorporates 3D-printed connectors that are a pivotal component of this cutting-edge concept [1-95].

In another development, *LACRIMA's* 3D-printed beehives can be integrated into sustainable farming practices by encouraging local production, reducing transport emissions and using recyclable materials[1-95]. They can also form part of integrated pest management systems, reducing the need for chemical treatments. *LACRIMA's* 3D-printed hives uses a special, fully biodegradable material, a wood-based composite, which sets them apart from traditional hives and other 3D-printed solutions[1-95]. This material and the design of *LACRIMA's* wooden hive ensure not only environmental sustainability, but also excellent insulation and durability, creating an optimal environment for bees, improving their health and productivity [1-95].

Another example is Teyme. The Spanish company uses HP's Multi Jet Fusion technology to manufacture parts such as air outlet adapters and air blade positioners. These are included in the agricultural machinery production [1-95]. 3D printing makes it possible to rapidly, cost-effectively prototype tools and components specific to the needs of agriculture. For example, machine parts and irrigation equipment that can be adapted to each farmer's particular conditions [1-95]. They can even be spare parts for specific machines, such as tools that are no longer manufactured, but are still needed. Furthermore, production of these tools on site eliminates the need for the farmer to travel, and the waiting times that could interrupt farming activities [1-95]. Finally, the democratization of additive manufacturing can enable both small and large farms to use and benefit from the technology[1-95]. Internet of Things (IoT) sensors and devices for monitoring soil conditions, factors such as moisture, wind and weather, can be 3D printed [1-95]. They are integrated into intelligent agricultural systems to improve crop decision-making[1-95].

Some drones and agricultural robots have been 3D printed[1-95]. They marked a milestone in the implementation of automation technologies in the field. In recent years, it has been demonstrated that these devices can perform tasks such as crop monitoring, seeding, the precise application of fertilizers and pesticides [1-95]. For example, Italian company Soleon, which specializes in unmanned aerial applications and drones, called on Materialise's additive manufacturing services to create the Soleon Dis-co[1-95]. Tackling the problem of the European corn borer, a pest that can wipe out a large proportion of crops, Soleon and Materialise designed a pesticide delivery system. However, they used Trichogramma eggs, a species of wasp that feeds on the European corn borer, which provided a natural solution. In this case, the drone was printed in PA12 using the SLS process[1-95]. 3D printing can also be used to create biodegradable containers or pots for seeds or seedlings. Thus making planting easier and reducing environmental impact[1-95].

For food production, farm equipment, farming products, 3D printing could be a great asset and simplify a lot of processes [1-95]. 3D printing is the perfect tool for mass-customization [1-95]. Indeed, this technology is perfect to create custom-made objects for many different sectors such as medical or automotive [1-95]. For agriculture, this mass-customization aspect is also a great advantage[1-95]. Indeed, it is particularly convenient to get 3D printed tools [1-95]. Indeed, using digital manufacturing is a great way to manufacture objects that have been designed perfectly. Moreover, this technique can be used both for prototype and production [1-95]. Indeed, 3D printing is a great asset for prototyping process but is now becoming an amazing production technique for various projects, as new resistant 3D printing materials are now available in the market [1-95]. Moreover, 3D printing is really a great advantage as farmers can really print devices on demand [1-95]. It is especially useful to print devices in remote areas. Additive manufacturing is a great technique to improve some processes that are already existing. It can help farmers to manufacture traditional equipment and tools[1-95]. That is exactly the technique used by farmers in Myanmar. They were first using CNC machines to prototype their tools, but it was quite slow and expensive [1-95]. Including the 3D printing technology in their production process helped them to create quality tools more quickly and improved their manufacturing process [1-95]. Hence, they can totally adapt the tools to their use and improve their farming activities. Moreover, for this kind of use, desktop 3D printer are great because they allowed them to print directly on place[1-95]. In some African countries such as Togo, farmers still have a difficult access to mechanized equipment. Sénamé Koffi Agbodjinou, founded an African digital fab lab, he designed a 3D printer and built it only using waste and electronic components he found in the street [1-95]. This 3D printer is working perfectly and helped local farmer to prototype their own tools. This additive manufacturing technology actually boosts their crop yields as they are free to produce all the tools that they need [1-95].

The company Farmshelf has developed an autonomous system allowing anybody to start a smart indoor farm[1-95]. Developing a new business is hard and quite expensive. Therefore, 3D printing for some entrepreneurs are able to save time and money by using additive manufacturing to develop some parts of their project [1-95]. 3D printing allowed them to design the right parts for their project like mounting brackets and plant hangings[1-95]. They were able to print custom parts quite quickly and test them. This would have been more expensive and would have taken more time with traditional manufacturing technique such as injection molding [1-95]. With the quick evolutions made in the 3D printing industry, it will be soon more convenient to 3D print large parts like these only in one time [1-95].

Canada-based company has produced 3D printed parts in order to help to test a high-technological crop seeding system [1-95]. Additive manufacturing is really useful for the Research and Development department, allowing to test a whole device and created many developments in order to develop the best product possible[1-95]. A lot of applications are already possible in the farming sector using 3D printing, but it will certainly evolve in the upcoming years and become even more integrated into agriculture [1-95]. Indeed, this technology has many benefits to bring to the farming sector, from tools to more elaborated devices[1-95]. Hence obviously need more 3D printers in agriculture, the use of the 3D printing technology needs to be developed [1-95]. For example, 3D printing could be a great solution to recycle plastic or metal materials laying around a farm. These materials could totally be used to recreate new tools or any other useful 3D printable device[1-95].

Even though 3D printing has already been a success for many applications in the farming sector, it will continue to evolve in upcoming years and become even more integrated into the agriculture industry[1-95]. This technology has many benefits to bring to the farming sector, from tools to more elaborated devices [1-95]. The 3D printing industry still has a lot to offer to agriculture as the technology continues to be developed, and it is anticipated to grow in popularity as farmers continue to reap the many benefits[1-95].

Additive manufacturing is delivering enhancements in structural operations, replacement parts for equipment, and the day-to-day tools and fixtures required by farmers [1-95]. 3D printed tools are becoming more commonly used to plant crops since they may greatly improve efficiency and customization [1-95]. These technologies are created rapidly, efficiently, and remotely to provide benefits on all levels, including energy and cost reductions while cutting lead times [1-95]. Managing farming equipment such as tractors, harvesters, seeders, and fertilizer spreaders is no mean feat - it is huge, complicated and costly, and consequently, changing a part can quickly become financially draining, particularly if the machine is obsolete and replacement parts are no longer accessible or difficult to obtain[1-95]. These replacement components may be manufactured quickly using 3D printing methods, reducing downtime, which is significant as agricultural applications are sometimes time-dependent due to weather variations and how crops must be processed to keep the fields on schedule[1-95].

While 3D printing is already being utilized in a variety of ways in agriculture, there is great potential for additional uses[1-95] including 1) Biodegradable plastics, reducing waste and enhancing agricultural sustainability. 2) Sustainable housing for livestock and other animals, boosting comfort and lowering agriculture's environmental effect. 3)Customized structures for vertical farming, allowing for crop production in urban locations and minimizing land-intensive agriculture. Other applications of 3D printing in agriculture are, 1) Increased efficiency: 3D printing can be used to create customized tools and parts, proving the efficiency and accuracy of agricultural operations.

2) Improved sustainability: 3D printing can be used to create biodegradable plastics and their sustainable products, reducing the environmental impact of agriculture. 3) Better animal welfare: 3D printing can be used to create customized prosthetics and orthotics for livestock, improving their health and well-being[1-95]. 4) Increased innovation: 3D printing enables new and innovative products and technologies in agriculture, providing new opportunities for sustainable and ethical food production[1-95].

The potential for 3D printing in agriculture is extensive and compelling, and as the technology advances, it will undoubtedly play an increasingly crucial part in determining the industry's future[1-95]. Along with adjustable farming equipment and autonomous agricultural instruments like drones and robots, 3D printing offers real-time data on plant health, nutrient levels, and soil state [1-95]. According to the study, AI and 3D-assisted IoT sensors [96-100] can help to increase yield by 10 % to 15 % while significantly reducing crop deterioration[1-95]. They can also help to reduce water usage by 20 % to 25 %, labour requirements by 20 % to 30 %, and overall power consumption by 20 % [1-95]. However, high costs, complex technical, design knowledge, and limitations on production speed and scale are obstacles to broader use. It is also necessary to handle safety and regulatory concerns[1-95].

3D printing has a promising future in various fields from advancements in bioprinting, multifunctional materials, blockchain, and artificial intelligence integration [1-95]. These advancements could boost 3D printing's potential and resulted in higher output, more sustainable practices, and higher-quality products[1-95]. Owing to this complex, personalized, and very precise components can now be produced, and this has transformed a number of industries, including agriculture, food, the aerospace, automotive, and healthcare sectors[1-95]. The potential of 3D printing has expanded into the food processing and agriculture sectors in recent years, offering to improve efficiency, sustainability, and product quality while addressing a number of issues these sectors encounter [1-95]. Additive manufacturing, also known as 3D printing, is an amazing innovation with a wide range of uses in intelligent agriculture and food processing[1-95]. Along with adjustable farming equipment and autonomous agricultural instruments like drones and robots, it offers real-time data on plant health, nutrient levels, and soil state[1-95].

However, 3D printing also faces some challenges, such as technical limitations, regulatory issues, and social acceptance that need to be addressed before it can be widely adopted in the agriculture sector [1-90]. India has seen increasing adoption of 3D printing technologies with growth rates over 30% year-on-year across materials [1-95]. The STPL3D, one of the major 3D printer manufacturers in the India and the first to create their own "Made-in-India" SLS 3D printer [1-90]. They are of the opinion that "Starting with first tier cities like Delhi, Mumbai, Bengaluru, Surat, Hyderabad, Coimbatore, and Pune, the demand for 3D printers in India is beginning to pick up[1-90]. Currently there are a number of different 3D printing technologies in India including extrusion, vat photopolymerization, selective laser sintering and selective laser melting (metal) [1-90]. Selective laser melting especially has received significant attention with India's largest 3D printing service bureau, Wirpro, recently investing in the SLM systems[1-93]. Indeed, it seems all current AM processes can be found in some form in the country, including the recent development of an Indian EBM 3D printer, though certain remain more popular than others [1-92]. The country has also become a hub for construction of 3D printing. Additive manufacturing is gradually reaching farms, and helping the sector to increase productivity [1-90]. It allows agriculture companies and farmers to build customized tools for their different farming needs[1-95]. Indian startup **Garuda3D** builds 3D printers to print hand tools[1-90]. The startup's 3D printing solutions assist farmers in developing various agricultural prototypes and production parts. It offers a 3D printed tri-claw fruit picker, shovel handle, garden hose splitter, drip irrigation structures, and sprinkler system. In addition to reducing costs, the startup's tools also increased productivity in the agriculture sector[1-92]. One major benefit of 3D printing for agriculture is that it can significantly reduce the expenses and downtime associated with traditional manufacturing and equipment maintenance [1-90]. On-demand production of customized machinery parts eliminates the requirement for substantial spare part stockpiles. Small-scale farmers, who might not have the means to maintain large stockpiles or wait for drawn-out supply chains to deliver critical parts, will especially benefit from this capability. Because 3D printing technology makes it possible to create specialized farming tools and equipment, the agriculture industry is undergoing a fundamental transformation [1-90]. In order to handle the unique requirements of various crops, soil types, and agricultural techniques, customization is essential for increasing productivity and lowering expenses[1-90]. Therefore, utilization of artificial intelligence (AI) and 3D-assisted Internet of Things (IoT) sensors can enhance agricultural output by approximately 10-15 %[1-95]. This technology also leads to a substantial decrease in crop spoilage, decreasing it significantly. Additionally, it reduces water usage by around 20-25 % and decreased the labour requirement by about 20-30 %. Overall, the power consumption is reduced by almost 20 %. With the progress in bioprinting, multifunctional materials, blockchain, and artificial intelligence integration, 3D printing is poised for significant growth in these areas, resulting in enhanced efficiency, environmental friendliness, and improved product standards.

5. Role of 3D Printing in Food Industries

One of the most exciting uses of 3D printing in the food processing industry is the development of customized nutrition plans [93-111]. 3D food printing (3DFP) has the main objective of tailored food manufacturing, both in terms of sensory properties and nutritional content [93-95, 101-103]. 3D printing has reinvented food processing by enabling personalized nutrition solutions, particularly in the field of medicinal nutrition [93-111]. It also makes it possible to alter the textures and structures of food, creating novel sensory experiences and better-quality goods [93-111-121]. 3D printing contributes to sustainable food production by reducing food waste (10–30 %) and using alternative protein sources [1-95]. Personalized 3DFP refers to special dietary necessities and can be promising to prevent different non-communicable diseases through improved functional food products, containing bioactive compounds like proteins, antioxidants, phytonutrients, and/or probiotics [93-111-121]. 3D printing can be used to create foods like meat, fish, pasta, pizza, chocolate and more. Companies like Nourished are using 3D printing to create personalized vitamin gummies. Each gummy can be tailored to meet individual nutritional needs, providing a custom blend of vitamins and minerals in one tasty bite [93-111].

When it comes to the food sector, worldwide applications of 3DFP can be related to chocolate figures, cookie dough, and cheese profiles, elaborated by a group of students, in 2006, when the first multi-material 3D printer was used to obtain different food products [93-111-121]. 3DFP is the development of food products using the techniques of AM. The 3D printers have pre-loaded recipes in their software, which allows the user to remotely design the products on their smart devices (e.g., phones, computers) [93-95, 101-103]. Most frequently, the printing material is held by the syringes and is stratified layer by layer through a nozzle to obtain the shaped final food product [93-95, 101-103]. This mechanism provides the possibility of integrating bioactive components (e.g., carotenoids, anthocyanins) into food stuffs to obtain a suitable diet for people with specific nutritional needs [93-111]. Various meals can be obtained in different shapes and colors [93-95, 101-103]. 3DFP technology can be adjustable for people with special diets, like pregnant women, astronauts or vegan/vegetarians [93]. Another advantage of 3DFP technology is related to the development of a variety of functional food products, by integrating diverse ingredients [93].

3DFP can be utilized to develop a personalized nutrition for people with special dietary necessities [93-111]. This means that the selected ingredients, introduced in the 3D printer to compose the meal, have a specific contribution, and are tailored for the individual's nutritional needs [93]. For example, a person with chronic kidney disease needs a meal with low potassium content, therefore 3DP offers the possibility of integrating only this kind of ingredients into the meal, and have it delivered in a personalized form [93]. Similarly, this technology can provide diverse food designs for people with chewing and swallowing struggles, giving them a different option for the "ice-cream-scooped" pureed food [93-111].

3D printers create food products that cater to a person's dietary requirements and tastes by carefully regulating the ingredients and their proportions [93-111]. The potential applications of 3D printing in smart farming and food processing are endless which creates continuous technological breakthroughs and creative integrations [93-95, 101-103]. 3D printing has a promising future in various fields' medical, agriculture, building construction to advancements in bio-printing, multifunctional materials, block chain, and artificial intelligence integration [93-111]. Sensorial proprieties, texture, and structure of 3D-printed food play an important role in the acceptance of 3D food products.

These advancements could boost 3D printing's potential and resulted in higher output, more sustainable practices, and higher-quality products [1-95]. Other printers were used to create sculptures from cookie batter, mashed potatoes, crushed nuts, or thin-layer foodstuffs, like pancakes [93-111]. 3DFP has as its main purpose tailored manufacturing of food in terms of sensory properties and nutritional content, at the same time [93-95, 101-103]. Additionally, in the context of the circular economy strategies, food waste could be decreased through the use of agro-industrial by-products in printed nourishment [93-95, 101-103]. However, limitation of product size, deficiency of standard process control, partial availability, and the high fee of materials are the factors that might limit its evolution, per general [93-111].

The advancement of 3DP technology has gained importance in the fields of the food industry as well as in gastronomy [93]. The engineering concept of 3DP is based on a controlled robotic process with dedicated software (generally a Computer- Aided Design) that builds up the product, allowing designers to create a prototype in a short time, with a specific format (e.g., STL) [93-113].

Three-dimensional printing is one of the most precise manufacturing technologies with a wide variety of applications [93-113]. Three-dimensional food printing offers potential benefits for food production in terms of modifying texture, personalized nutrition, and adaptation to specific consumers' needs, among others. It could enable innovative and complex foods to be presented attractively, create uniquely textured foods tailored to patients with dysphagia, and support sustainability by reducing waste, utilizing by-products, and incorporating eco-friendly ingredients [93-113]. Notable applications to date include, but are not limited to, printing novel shapes and complex geometries from candy, chocolate, or pasta, and bio-printed meats [93-113]. The main challenges of 3D printing include nutritional quality and manufacturing issues. Currently, little research has explored the impact of 3D food printing on nutrient density, bioaccessibility/bioavailability, and the impact of matrix integrity loss on diet quality. The technology also faces challenges such as consumer acceptability, food safety and regulatory concerns. Possible adverse health effects due to over consumption or the ultra-processed nature of 3D printed foods are major potential pitfalls [93-113-121].

According to Varvara et al., (2021) [93], 3DFP is an expanding area of food processing and gastronomy with very diverse possibilities to branch out much further, from personalized nutritional care food products to tailored food products to deal with specific ailments [93]. The critical factors influencing consumer acceptance over novel food formulations is related to the food aspect (color, shape), sensory properties (flavour, texture), nutritional composition (macro- and microelements), and costs. Currently, most scientific research focuses on structure and composition, being in an incipient stage of developing the concept of 3DFP [93-111]. Thus, for a general acceptability of the concept, it would be desirable to analyze consumer preference related to the new ingredients and their functionality [93]. Simultaneously with the sensory analysis (e.g., hedonic tests) of the 3DP food products, the consumer has to be informed about the whole printing process and the beneficial effects of functional foods on health [93-111].

Varvara et al., (2021) [93] also confirmed that any type of functional ingredients can be integrated in new food products, as long as an appropriate powdered form of the matrix is developed (mash size of the particles, dried powdered), and the suitable 3DFP technology is selected (e.g., extrusion, SLS, HAS, or binder jetting) [93]. Furthermore, regarding the circular economy action plan of the European Union, bioactive compounds recovered from diverse agro-industrial by-products can be incorporated, like pectin from apple wastes, chitosan from crustacean processing, and carotenoids from tomato agro-industrial by-products [93]. At the same time, these ingredients can add value to the new food products through their biological activities, like antioxidant properties, antimicrobial and anti-inflammatory functions, fulfilling the purpose of sustainable bio-economy [93].

According to a study by Singh & Sit in 2022[18], 3D printing could create plant-based meat analogs with mouthfeel and textures that are quite similar to actual meat [1, 12, 18]. By using alternate protein sources and minimizing food waste, 3D printing helps to make food production more sustainable [1-95]. For instance, 3D printing can be used to transform insects, algae, and lab-grown cells into appetizing meals, offering sustainable substitutes for conventional protein sources [1-95]. Furthermore, 3D printing reduces waste by using extra and wasted materials to make new food products [1-95].

3D printing has the capacity to transform smart farming and food processing through the provision of specialized instruments, precise monitoring systems, customized meals, and eco-friendly procedures [1-95]. 3D printing enables the development of personalized nutrition solutions, especially in the field of medical nutrition, at the food processing stage. Additionally, it enables the alteration of food structures and textures, leading to novel sensory encounters and superior-quality products [1-95]. Through the utilization of alternative protein sources and the reduction of food waste by 10- 30 %, 3D printing contributes to the advancement of sustainable food production [1-95].

While there are many varieties of food printers, the most in use is the extrusion type, where the ink is pre-mixed and of a consistency that is extrudable through the nozzle [1-95]. It cannot be as watery as dosa batter, because it will flow before the next layer can be printed on it [1-95]. It cannot be of the consistency of chapati dough either, as that is not easily extrudable [1-95]. Natively printable materials, like chocolate, hummus and peanut butter, are the easiest to work with 3D printing [93]. A big chunk of ongoing research across the world aims to create newer food inks, making natively unprintable materials, like proteins and fibres, printable [1-95]. This is done through various methods, like adding edible gums, hydrocolloids or oleogels [1-95]. 3DFP has immense potential to provide a better solution for customized shape, texture, and personalized nutrition [1-95]. It involves a basic understanding of the printability of the material, i.e. the food chemistry along with *the* processing and techniques to create customized healthy food [1-95]. Despite offering promising avenues to enhance aspects of gastronomy, 3DFP nowadays is not widely used in this context [1-95]. In addition, the number of studies investigating the use of 3DFP to create gastronomic experiences is limited [93]. Advancing the area of 3D printed foods offers opportunities for generating new types of gastronomic experiences that are not only esthetically pleasing, but can also contribute to social, and environmental sustainability, by reusing food waste or activating consumer interest and desire for healthy food [1-95]. However, the maturity of 3DFP to date is still in its infancy and studies have thus far been limited in investigating 3DFP based on isolated pillars such as technical characteristics[1-95].

The rising threats to food security include several factors, such as population growth, low agricultural investment, and poor distribution systems [1-95-111]. Consequently, food insecurity results from a confluence of issues, including diseases, processing limitations, and distribution deficiencies [1-95-111]. Food insecurity usually occurs in vulnerable areas where certain technologies and traditional food safety testing are not a viable solution for food borne disease detection [1-95]. In this regard, 3D printing technologies and 3D printed sensors open the platform to produce portable, accurate, and low-cost sensors that address the gaps and challenges in food security [1-95-111]. Hence the perspective role of 3D printed sensors in food security in terms of food safety and food quality monitoring to provide reliable access to nutritious, and affordable food [1-95]. Recent developments in robotic technologies for mechanization, such as food handling with soft grippers, are also playing an important role in food industry [1-95-111].

In the rise of the industrialization era, food production has increased because of the feasibility of mass production using state-of-the-art technologies [1-95]. It is a stepping stone toward more stable, sustainable food production by addressing the crisis caused by the population growth, low agricultural investment, and poor distribution systems [1-95]. Also, due to advancements, food shelf life can be extended. Insect infestation has been a challenge to agricultural products since ancient times, but the formulation of pesticides and herbicides has aided pest management [1-95]. However, in the process, hazardous contaminants and high level preservatives were also introduced that impose threats for securing safe and nutritious food [1-95]. Traditionally, analyzing food contaminants was performed in laboratories; however, such testing is time-consuming, requires trained personnel to evaluate the results, and is expensive [1-95]. These conventional assessment methods are not suitable for the rapid, noninvasive, and convenient analysis used in the assessment of food safety [1-95]. Recently, 3D printed sensors have demonstrated a potential in providing on-demand technology as it synthesized the production of low-cost, reliable, and accurate sensors[1-95]. The presented advantages of 3D printing methodologies have drawn attention for utilization in a wide range of applications. 3D printed sensors and devices are seen in multiple key food sectors, such as agriculture, water security, food processing, and food handling [1-95]. The act of providing accurate and inexpensive technologies is needed to detect imminent threats in food security [1-95].

The trends toward favoring 3D printing manufacturing over traditional sensor fabrication methods are evident due its advantages. [93]. The simplicity of multimaterial printing addresses challenges in integrated sensor fabrication, particularly in the production of electrochemical sensors crucial for highly functional printed sensors deployed in food safety and quality monitoring[1-95-111]. Moving forward to the integrated use of 3D printing technology, it is poised to revolutionize not only food safety assessments, quality monitoring, and processing but also the broader landscape of intelligent farming and processing [1-95]. The synergy between 3D printed devices, artificial intelligence, and Internet of Things (IoT) technology introduces intelligent opportunities for smart processing and farming. [96-100]. The flexibility and customization offered by 3D printing sensors integrated into systems exhibit limitless potential across various fields, promising enhancements in every aspect of food security[1-95-111]. As challenges in large-scale manufacturing using 3D printing technologies are systematically addressed, there is an expanding path toward future applications and innovations that focus on food production and security [1-95-111].

In the past seven years, Indian researchers have experimented extensively with 3DFP [93]. They created healthier snacking options like a fibre-fortified chicken lollypop for children (*bit.ly/chicken-lollypop*) [93]. They took discards from other food-processing streams and up scaled them into nutrition-packed snacks — noodles printed from an ink of potato peels, cookies made from the pomace of grapes after the juice was extracted, and protein bars from peanut protein cakes left after the extraction of oil (*bit.ly/peanut-print*) [1-95]. In another development, A research group at the Indian Institute of Technology (IIT) Mandi is working on applying these advanced methods to develop a matrix system to control the quality of printable food on four counts: texture, taste, colour, and calorific value [1-95]. The team has developed a zero-calorie food ink with nanoparticles of functional foods and cellulose that can be used to make waffles or pancakes, and are now applying for a patent [1-95]. Changing consumer demand and unstable supply chains create challenges in the food and beverage (F&B) industry. Start-ups are integrating 3D printing for product development and production lines to optimize processes for the F&B industry. For example, such 3D food printers feature pre-loaded recipes that allow users to remotely create food. Moreover, this allows food developers to integrate food production with computers, smart phones, or internet of things (IoT) devices[1-95-111]. Laboratories across the globe are working on enhancing taste, making healthier options and more complicated structures using 3DFP [93-111]. Last year, engineers at Columbia University printed a cheesecake with seven ingredients/inks, each in a different layer. But the technology is yet to catch up commercially. Researchers are ready with the R&D. Across the world, around 300 food products have been printed; now the big breakthrough will happen when the industry is willing to invest in the technology [1-95]. Canadian startup Devoray uses 3D printing to produce food in any shape. The start-up offers a machine, as well as the necessary guidance, to print beverages ranging from cocktails to sports and nutrition drinks. By mixing alcohol and water with Devoray's 3D printed ready-to-mix products, consumers are able to create beverages in as little as thirty seconds [1-95-121]. Consumers are becoming more aware of the ecological and ethical impact of meat consumption. Consequently, they are looking for alternatives that provide the same taste without compromising on nutrient and protein consumption. To this end, start-ups and scaleups offer 3D-printed alternatives to meat. Israeli start-up SavorEat develops a plant-based meat alternative that possesses the same texture and taste as natural meat[1-95]. The start-up combines additive manufacturing with a robot chef to create dishes. It uses plant-based ingredients and provides the ability to cook or grill the product simultaneously with the printing process [1-95]. In comparison to conventional cooking methods, this process improves the flavor profile of plant-based meat[1-95-111-121].

Balanced nutrition is essential to remain healthy. However, today's fast-moving lifestyle makes it difficult to maintain a balanced diet [93-111]. Additive manufacturing offers ways to create food more efficiently while increasing the nutritional value [1-95]. Start-ups already manufacture machines that print food, beverages, and pills on-demand. These machines comprise food-grade syringes or cartridges that hold real food items and deposit exact fractional layers to create a complete meal [1-95-111]. British start-up Nourished provides freshly made vitamins using additive manufacturing. It encapsulates natural ingredients into a vegan hydrocolloid gel to offer tailor-made nutrition on-demand. The start-up offers 30 different vitamins, minerals, and supplements to suit the needs of different consumers[1-95-111]. For example, Nourished's solution incorporates sweet, sour, or fruit flavours as coatings over their gummy vitamins stack. The coatings are also sugar-free, natural, and gluten-free [1-95]. When it comes to food, customization is the key to gain a competitive edge in the industry. 3D printing saves both time and energy when it comes to experimenting with different types of food dishes [1-95]. It also helps in creating intricate detailing to make the food look more appealing with less effort[1-95-111]. Start-ups provide restaurants with food printers that create dishes according to a customer's choice[1-95]. Bulgarian startup Chocola3D offers 3D printers that print chocolates, doughs, cheese, meat, vegetables, and fruit pastes [1-95]. The printer nozzle's diameter comes in 0.7 mm and 0.9 mm [1-95]. The printers feature a flash drive and allow for remote control as well. With a printing speed of 50 mm per second, the startup provides chefs with the flexibility to experiment and create dishes more efficiently[1-95]. The 84 3D food printing start-ups, focus on alternative protein, 3D printed supplements, as well as personalized products or processes. While all of these technologies play a major role in advancing FoodTech, they only represent the tip of the iceberg [1-95-111].

According to Derossi et al., (2024) [95], 3Dprinting is an on-demand technology that can benefit the sustainability of the food sector [1-95-111]. The emerging world of 3D-printed foods is growing rapidly because it offers new ways to reshape how foods are manufactured and consumed [95]. Digitally designing a 3D food model and replicating it by depositing food components in a layer-by-layer process has many beneficial impacts[95]. Unprecedented and modulable/customizable interactions between sight, hearing, smell, and touch and food products can maximize sensory acceptance and can sustain the adoption of a healthier diet and food waste reduction [95]. The high freedom of movements of 3D printing enables the creation of complex shapes and internal structures, which offer the opportunity to reduce mastication and facilitate swallowing for the elderly, modulating satiety, reducing the intake of calories, salt, and sugars, and controlling the release kinetics of nutrients [95].

5.1. **Types of 3D Food Printing**

Four main forms of 3D printing of food products have been introduced, which include extrusion, inkjet printing, binder jetting, and powder bed melting through selective laser sintering [95-113]. All forms are dependent on the use of 3D computer-aided design [95-113]. An extrusion method is a common approach in 3D food printing [95-113]. The extrusion technique allows fresh ingredients, or pre-processed ingredients, to be printed layer by layer and deposited onto a platform until the designed 3D structure is shaped [95-113]. Inkjet printing is used for low-viscosity materials, so it is primarily used for 2D printing, such as creating high-resolution images on cookies [95-113]. Binder jetting and selective laser sintering work primarily with powder-based materials, where the powder particles combine in the presence of heat or liquid as a binding agent [95-113].

5.2. Advantages of 3D Food printing

1) Precision: 3D printing allows for precise measurements and designs, which can be difficult to achieve by hand. This precision can lead to more consistent results and higher-quality dishes. 2) Creativity: 3D printing opens up a world of possibilities for chefs and food enthusiasts to create unique and intricate designs that were previously impossible to achieve by hand. 3) Efficiency: 3D printing can save time and reduce waste in the kitchen. Chefs can print exact portions of ingredients, reducing the need for excess ingredients and minimizing food waste. 4) Accessibility: 3D printing can make cooking more accessible to people with disabilities or physical limitations. For example, a person with limited mobility may find it difficult to chop vegetables, but with a 3D printer, they can print pre-chopped vegetables in the desired shape and size.

Three-dimensional printing is a promising novel technology in the field of food and nutrition. Three-dimensional printed food has potential applications in the field of nutrition, including the production of visually appealing modified-texture diets, personalized nutrition, supporting sustainable development and mitigating food insecurity. Threedimensional food printing is fast and easy, and operators can produce printed food by simply learning parameter settings or downloading electronic recipes directly. Many 3D food printers are already available for professional, industrial, and domestic use, and in the future may become suitable for producing ready-to-eat foods that meet individual nutritional demand through devices such as vending machines connected to personal workout APPs.

6. Limitations of 3D printing

However, there are several challenges that need to be addressed, including significant initial expenses, the need for specific expertise, limitations in production speed, and concerns related to safety and regulatory compliance[1-95-111]. To establish comprehensive regulatory frameworks, sustain technical advancements, and promote collaboration, it is imperative for legislators, researchers, and industry players needs cooperation [1-95-111]. The utilization of 3D printing in agriculture and food processing is anticipated to completely transform these industries, resulting in substantial improvements in consumer contentment, efficiency, and environmental responsibility. The development of bio-printing, multifunctional materials, and integration with block chain and artificial intelligence is driving the enormous potential of 3D printing in smart farming and food processing in the future [1-95-111].

Even though the advancement of foods printing technologies has noticeably increased, however some of the challenges and limitations of food 3D printing should be addressed. Food 3D printing is yet inadequate way for massive food production, since it is a slow manufacturing process, and has high production costs (for large quantities). As a result, few have engaged food printing in real-life scenario. Consequently, food 3D printing technology is typically used in prototyping, research, or in special cases like food for space [1-95-111]. Furthermore, varied recipe mixing methods are still an ongoing concern in food 3D printing. Likewise, researchers and developers must consider the various material characteristics of food as well as dietary quality.

Following are the few important limitations of 3D printing.

1) According to Qi (2023) [2] one of the biggest challenges of 3D printing in agriculture is the cost [2]. The equipment and materials needed for 3D printing can be expensive, making it difficult for small farmers to invest in the 3D printing technology [2]. 3D printer can cost anywhere from $200 to $10,000, depending on the size, quality, and features[2]. The materials used for 3D printing, such as plastic, metal, or ceramic, can also be costly and may require special storage and handling [2]. Additionally, 3D printing can consume a lot of energy, which can increase the operational costs and the environmental impact of the technology [2]. 3D printers can be expensive, making them inaccessible to many people. The cost of materials used in 3D printing can also be high.

2) According to Qi (2023) [2], 3D printing technology can be complex and challenging to use, especially for farmers who may not have prior experience with the technology[2]. 3D printing requires a digital design of the object to be printed, which can be created using Computer-Aided Design (CAD) software or scanned from an existing model[2]. However, creating or modifying a digital design can be time-consuming and require technical skills and knowledge [2]. Moreover, 3D printing involves various parameters and settings, such as the temperature, speed, and resolution that can affect the quality and accuracy of the printed object. Therefore, 3D printing may require training and support for farmers to use the technology effectively and efficiently[2].

3) Another limitation of 3D printing in agriculture is the quality and durability of the printed objects[2]. According to Qi (2023) [2], 3D printing can produce objects with intricate shapes and structures, but it may also introduce defects and errors, such as cracks, warping, or porosity, that can compromise the strength and functionality of the objects[2].

4) Another limitation of 3D printing in agriculture is the regulation and standardization of the technology[2]. According to Qi (2023) [2], 3D printing can raise various legal and ethical issues, such as the intellectual property rights, the liability, and the safety of the printed objects. These are some of the limitations of 3D printing in agriculture that may affect its potential and impact [2]. However, 3D printing also has many advantages and opportunities for agriculture, such as cost reduction, availability improvement, customization, enhancement, and performance improvement. According to Qi (2023) [2], 3D printing is a potential technology that can revolutionize the agriculture industry by impacting the design and performance of agricultural machinery and products [2].

5) However, low printing speed, lack of a system for multi-material deposition, inconsistency in printing performance of the food formulas, the difficulty of printing multi-ingredient ink-food due to difficulty of estimating the rheological properties when changing the food formula, and the limited information regarding the safety and the shelf life of 3D printed products, still hamper the widespread use of 3DFP in gastronomy and at industrial levels [95, 112].

6) Some argue that 3D printing removes the human element from cooking, an essential part of the culinary experience. Cooking is not just about taste but also about the process and emotions of creating a dish. Therefore, 3D printed food is not tasty. While 3D printing allows for intricate designs, it may not always be the best-tasting dish. The focus on design may take away from the taste and texture of the food [112].

7) There are concerns about the safety of 3D-printed food. The materials used in 3D printing may not be food-grade, and there is a risk of contamination if the printer is not properly cleaned [112].

8) Due to 3D-printed food's niche market and lack of wide-spread use, ingredients made specifically for these foods are scarce, and there are not many manufacturers of food-ink ingredients.

9) The realization of the above applications in the field of 3D food printing for nutrition still faces many challenges, including the stability of 3D printed food, gaining consumer trust, and a better understanding of the nutritional impact of printed food on nutrient density and bioavailability [95-113]. Once these challenges are overcome, 3D food printing technology can be more widely used. However, once 3D printed foods are accepted and widely used by consumers, their overconsumption may cause adverse health consequences due to ultra-processing, usage of food additives, and destruction of the food matrix[95-113]. Three dimensional printed food may also affect present dietary traditions, possibly reducing diet quality[95-113].

10) Currently, 3D Printing has to shift from a focus on printing snacks to printing more nutritious foods; the emphasis should be placed on improving the nutritional quality of printed foods [95-113]. More research is needed regarding the nutrient profiles, density, and bioavailability of 3D printed foods, or the health impact of the possible loss of food matrix, such as the effects on the gut microbiome and glycemic response [95-113].

11) More clinical research is also needed on the nutritional therapeutic effects of 3D printed texture modified foods on people with swallowing difficulties [95-113]. Future research should be conducted on the possible applications of 3D printed food in healthcare, such as complementary foods for infants according to developmental stages, supplementary foods for elderly in long-term care, a variety of patient-oriented foods in hospitals, and food products for anorexia, allergies, and intolerances [113].

12) Among the main obstacles are technical complexity, high equipment costs, and limited public acceptance due to a lack of awareness about the benefits of 3D printing [117]. Additionally, issues related to food safety, process standardization, and scalability must be addressed for the technology to achieve widespread adoption. The extrusion technique has been widely used due to its flexibility in handling viscoelastic formulations [117]. However, further exploration of other techniques for food production, such as stereolithography and selective laser sintering, is necessary to expand application possibilities, particularly in creating foods with complex geometries or specific nutritional properties. It concludes that, despite current limitations, 3D printing has the potential to revolutionize food production by enabling the creation of products that meet the nutritional and sensory demands of modern consumers [117].

13) Although some people are open to food 3D printing, there were still others who were reluctant to try 3D printed food [116]. Therefore, it is necessary to improve some components of the 3D printed food for costumers to embrace [116]. For example: increasing safety, simplified 3D printing process, better shelf life of ink, etc

14) In extrusion-based technique, only screw-based and gear-based have continuous process, and both have their own limitation [116]. Therefore, new printers imposed new design for continuous process and without the drawbacks of screw-based and gear-based mechanisms[116].

15) By bioprinting cultured meat, couples of problems may be resolved, but the process of bioprinting for now is more expensive than traditional method[116]. Therefore, a search of economical and safe materials for bioprinting process is the key for market adoption[116].

16) Although some of the materials do not need an additive to be printed, some researchers still used it. The printing parameters also changed with each material, which made things more complicated [116]. Therefore, natural additives and a simple open cloud storage for saving printing parameters may be implemented[116].

17) A need for international standard for 3D food printers' company to meet safety standard of printed food[116].

18) Future regulatory frameworks should address the unique challenges of 3D food printing, such as the use of novel food inks and complex printing structures [116]. Potential guidelines could include standards for the development and testing of food-grade materials, the implementation of AI-driven monitoring systems, and protocols for the safe disposal of waste materials[116]. Collaborative efforts between regulatory bodies, industry stakeholders, and researchers will be essential in developing these frameworks [116]. Using eco-friendly cleaning agents and sustainable materials for equipment construction, along with methods for managing waste generated from cleaning processes, can enhance the sustainability of 3D food printing [116].

19) Customized food printing is becoming rapidly popular among the many uses of 3D printing [116]. Foods, such as meat, chocolate, candy, pizza, cookies, and bread, can be manufactured layer-by-layer with 3D food printing technology while controlling the food's nutrient content, amount, and taste [116]. Most of the printing method/technique is using extrusion-based method due to its versatility [116]. However, even with it, only some types of food, for now, can be 3D printed [116]. Although progress has been made, food 3D printing is still not suitable for mass products, but this is not a serious problem, since food printing is for customization[116]. There is also a specific parameter for each type of food that may complicate the printing process, including the need for additives[116]. There is still a need to make a better extrusion process that can be used for a wide range of materials and that is continuous. Shortly, 3D food printing has many benefits to give, but in the implement stages, there are still a need for improvements[116].

7. Conclusion

3D printing, is the process of layer by layer building three-dimensional objects from digital models. Additive manufacturing, also known as 3D printing, is an amazing innovation with a wide range of uses in medical, intelligent agriculture and food processing. The agricultural sector, a cornerstone of India's economy, is witnessing a technological revolution. Three-dimensional printing (3DP), also known by the terms "Additive Manufacturing" (AM) or/and "Rapid Prototyping", is the process of making three-dimensional solid objects from a digital file fort. India's journey in the realm of 3D printing is inspiring and indicative of a promising future. From its modest beginnings in the 1990s to the vast ecosystem that thrives today, India's AM landscape has been shaped by innovation, strategic planning, and a confluence of public and private initiatives. The strategic alignment with national campaigns, such as 'Make in India,' underscores the nation's commitment to harnessing AM's economic growth and self-reliance potential. As sectors ranging from aerospace to healthcare embrace AM, India is poised to redefine global manufacturing paradigms. While challenges persist, the nation's adaptability, visionary mindset, and collaborative spirit signal a future where AM plays a pivotal role in India's socio-economic fabric.

3D printing has a promising future in various fields medical, agriculture, building construction to advancements in bio-printing, multifunctional materials, block chain, and artificial intelligence integration. This technology has the potential to help to solve environmental problems, enhance production, save expenses, and optimize resource management. The system provides up-to-date information on the health of plants, levels of nutrients, and the condition of the soil. It also allows for customization of farming equipment and includes autonomous agricultural instruments such as drones and robots. Three-dimensional food printing may improve the appearance of soft or pureed textured foods, which can help individuals with swallowing difficulties and prevent aspiration pneumonia caused by choking, as well as enhance patients' appetite and improve malnutrition. 3D printing has reinvented food processing by enabling personalized nutrition solutions, particularly in the field of medicinal nutrition.This novel technology also allows the creation of personalized foods based on individual nutritional needs, including customized individual supplements, customized patient-oriented diets, and personalized probiotics and nutrients enclosed into functional foods through microencapsulation technology. Incorporating new ingredients into conventional foods is also one of the promises of 3D food printing, which replicates the appearance of foods that have nutritional value but are not acceptable to consumers to increase acceptability and consumption. In addition, this technology may reduce regional food insecurity by increasing sustainable food sources, reducing food waste, and improving diet quality.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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