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3D Printing Applications in Agriculture, Food Processing, and Environmental Protection and Monitoring

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Abstract. 3D Printing, more formally known as Additive Manufacturing, is already being applied in many different applications. This paper presents a mini review of the use cases of 3D printing in the fields of agriculture, food processing, and environment protection and monitoring. Specifically, the paper discusses the different materials used in 3D printing of parts, the different printing technologies employed in the process, as well as the application prospects. PLA and ABS thermoplastics are the most common materials used for 3D printing in the field of agriculture as they are relatively cheap and easy to print. The direct extrusion of food helps people with swallowing difficulties increase their food intake as well as customize their diet. As for the environment, applications in water desalination and air quality monitoring are among the relevant applications of 3D printing presented in this paper.

Keywords: 3D Printing, Additive Manufacturing, Agriculture, Food, Environment

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1. Introduction

3D printing has been garnering increasing attention from different industries for its revolutionary impact in the field of manufacturing. It is set to gain mass adoption for its sustainable and efficient system of creating a variety of objects layer by layer using a 3D printer [1]. This technology greatly reduces waste and lead time in contrast to conventional manufacturing which includes subtractive manufacturing where a portion of a material is removed/subtracted from its greater part to produce a desired by-product. One of its advantages over formative manufacturing is its ability to produce complex shapes. The burden of high costs from traditional manufacturing is also considerably minimized through additive manufacturing [2].

Additive manufacturing has significant real-world applications in different fields such as in construction, electronics, automotive, personal protective equipment, astronomy, oceanography, military, and many others [3-9]. Moreover, additive manufacturing is becoming more prevalent in industrial applications requiring high performance such as in rapid prototyping, rapid tooling, rapid manufacturing [1,10,11,12,13,14], advanced electronics [4], medical applications [5], water filtration and desalination [14,15], and others. In agriculture, 3D printing finds most utility in the production of farming tools [16] and replacement parts [17] without greatly compromising their quality. The food industry mainly uses 3D printing to hasten to modify personal nutrition [18] as well as to help people with swallowing problems increase their food intake [19]. As for the environment, the production of recycled filaments [20] and of the parts of equipment used for air quality monitoring [21] and wastewater treatment device [22] are the relevant use cases of additive manufacturing.

There are a variety of materials and printing technologies associated with 3D printing. Fused deposition modeling (FDM) is one of the most popular 3D printing technology as it offers consumer-grade materials/filaments such as acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) thermoplastic [1]. Food can also be directly extruded from the printer nozzle as it is built layer by layer or it can be cast in a mold— as in the case for 3D printed puree [23]— created by a 3D printed pattern.

The recognition of the uses of 3D printing in many fields and industries is the future of manufacturing. It is a revolutionary technology where efficiency and sustainability go hand in hand that greatly improves our way of creating and producing things that have relevant use cases in a myriad of industries and fields. This review paper will provide an overview of the applications of 3d printing in the areas of agriculture, food processing, and environment protection/monitoring, as well as the technologies and materials being used.

2. Overview of Additive Manufacturing

3D printing generally goes through a 5-step process. First, a 3D model is generated with the use of computer-aided design (CAD) software. Such model is then converted into a Standard Tessellation Language (.STL) file so that a 3D printer can read its surface geometry. Subsequently, the model is sliced into multiple layers in order to feed printing instructions to the 3D printer. The model then materializes in the additive manufacturing system (3D printer) where the object is extruded layer by layer. Finally, post-processing is done in order to enhance the print quality of the 3D printed object [1].

There are many kinds of 3D printing technologies with different ways of manufacturing systems. Besides the extrusion-based FDM, stereolithography (SLA) is also a common 3D printing technology where photocurable resin is often used as the material. Compared to SLA, digital light processing (DLP) uses a projected digital image instead of laser which allows the printing process to proceed at a significantly faster rate. Selective laser sintering (SLS) uses laser as the heating source that selectively sinters the powder polymer such as resin or metal to create a 3D printed model. Other 3D printing methods include multi jet fusion (MJF), electron beam melting (EBM), direct metal laser sintering (DMLS), laminated object manufacturing (LOM), and others [1].

ABS and PLA thermoplastics are the widely used materials in 3D printing as they are associated with the consumer-level FDM printing technology [1]. These filaments are available in different colors and are recognized for their strength, stiffness, printability, cost-effectiveness, and other favorable properties that make them desirable materials for additive manufacturing [24]. Other materials include resin that presents high quality prints through smooth and transparent surfaces. Powders in the form of polyamide nylon is also commonly used for highly detailed and flexible printed objects [25]. Precious metals such as gold, silver, and brass can be used for jewelry applications [26].

3. 3D Printing Applications in Agriculture

3.1. Printing Technology and Materials

FDM is the commonly utilized printing technology in the production of different tools and equipment used in the field of agriculture. Thermoplastic, notably PLA and ABS, have found significant use cases in the production of farming tools such as sprinklers [27] and hose splitters used for irrigation [16], spare machine parts such as the corn auger [28] and gears [29], as well as in seed sowing equipment [30]. Farmers can also create customized tools using PLA such as a fruit picker and a shovel with the material being biodegradable and recyclable [16]. While these thermoplastics may differ slightly with their properties like stiffness and heat resistance, they are the most commonly used filaments in 3D printing owing to their (low) cost and straightforward use in 3D printing. Table 1 summarizes the application, material, and 3D printing techniques used in the field of agriculture.

3.2 Irrigation and Water Management

Most of irrigation and water management equipment could be manufactured using 3D printing; the garden hose splitter/adapter shown in Figure 1 is one such example [16]. The design of this supplementary equipment could be modified to allow multidirectional flow of water from a garden hose. Thermoplastic is the commonly used material to produce 3D printed objects and parts that can greatly help in water distribution systems in farms by replacing their costly, original parts. In this application, the PLA thermoplastic is the printing material used through fused deposition modeling.

The 3D printed spigot shown in Figure 2 is especially made for a 5 gallon bucket [16]. It is made of PLA thermoplastic through FDM. With additive manufacturing, the size and dimension of such tool can be customized accordingly with customized design and attachments such as a contour that fit the particular water container. The technology offers efficient and cost-effective production of these parts.

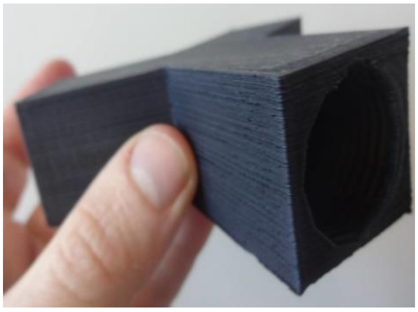

Figure 1. 3D printed garden hose splitter [16]

Figure 2. 3D printed spigot [16]

3.3 Urban Farming

While there are numerous innovations for optimized bulk harvesting, 3D printing can add value through a simple mechanism of clawing fruit that gathers high-hanging fruits without having to use ladders. The 3D printed parts of the tool can be incorporated with conventionally manufactured components like the wood handle, springs, and screws in order to make up the tri-claw fruit picker, as shown in Figure 3 [16]. Polylactic acid (PLA) proves useful in the material make-up of the parts created through fused deposition modeling as it is biodegradable and recyclable. This avoids unnecessary waste generated from conventional manufacturing, thereby promoting sustainability.

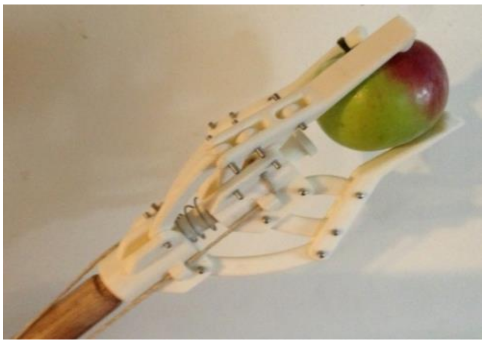

Figure 3. 3D Printed Fruit Picker [16]

Figure 4. Meat Slurry Puree [23]

Table 1. Applications, materials, and 3D printing techniques used for 3D printing in agriculture.

3D Printed Part	Application	Material/Filament	3D Printing Technique	Reference
Sprinkler	Irrigation	ABS	Fused Deposition Modeling	[27]
Hose splitter	Irrigation	PLA	Fused Deposition Modeling	[16]
Fruit picker	Urban Farming	PLA	Fused Deposition Modeling	[16]
Shovel and handle	Urban Farming	PLA	Fused Deposition Modeling	[16]
Packer bottom	Testing Equipment	ABS	Fused Deposition Modeling	[30]
Spigot	Water Management	PLA	Fused Deposition Modeling	[16]
Corn Auger	Spare Part	PLA	Fused Deposition Modeling	[28]
Gear	Spare Part	Polymeric material	Fused Deposition Modeling	[29]

3.4 Prospects

3D printing can stimulate youth entrepreneurship by designing and printing their own models and potentially taking advantage of the technology as an enterprise. Such businesses can also bring about collaboration among professional designers, entrepreneurs, and most especially farmers who are the primary beneficiaries of additive manufacturing in the field of agriculture. Research and development can be implemented to further increase manufacturing efficiency and quality as well as prospective materials that can be used alternatively for commonly established 3D printing materials such as thermoplastics [31]. With the advent of large format 3d printers, large parts with at least 1 cubic meter in size, can now be produced, which further expands the use cases of 3d printing. It is expected that in the future, other 3d printing technologies other than FDM will also be utilized.

4. 3D Printing Applications in Food

4.1 Printing Technology and Materials

Extrusion-based 3D printing, also known as FDM, is the most common printing technology in the food sector. 3D printing allows rapid manufacturing such as in making a cake layer by layer using a cake decorating robot [32]. Purees manufactured using 3D printing are mixed with a certain amount of thickening additives such as gelatin for the meat slurry [23] and pectin for the fruit-based snack in order to increase its print quality [18]. Mashed potato is printed from potato flakes with gelatinized starch, known as an ideal ingredient for the manufacturing of finished products for its lesser requirement in post-processing [33]. Vegetables such as carrots, peas, and corn can also be 3D printed as they are relatively easy to prepare and are inexpensive food inks [19]. Pizza [34], pasta [23], and dessert [35] can also be created directly using extrusion-based 3D printing. Table 2 summarizes the application, food ink, and 3D printing techniques used for the food sector.

4.2 People with Dysphagia

The 3D printed meat slurry shown in Figure 4 [23] is added with 100g of water and 40g of gelatin powder for better print quality. Moreover, it is designed in order to help people with dysphagia— a condition where there is difficulty in swallowing— to increase their food intake. The mixture of gelatin with the cooked meat slurry resulted in good print quality of the 3D printed food. 3d printing provides a novel way to produce instant and ready-to-eat food which can simulantaneously help consumers spend less than if the food is bought (physically) in a market. 3d printing also helps in devising a diet plan because the exact nutrional components can be manipulated before printing. Vegetables can also be additively manufactured as is the case for the 3D printed vegetables that are designs of garden peas, carrots, and corn. The selection of food ink with different nutritional components is enabled while maintaining the food's visual appeal for dysphagic patients to perceive such 3D printed food as no less different from tradionally-prepared food. Such extruded food are made to be soft in the pre-extrusion phase of the 3D printing process so that they can be made more chewable [19].

4.3 Personalized Nutrition

Personalized nutrition is also made possible with 3D printing. One such example of this is the 3D printed fruit-based puree snack made for the consumption of children aged 3-10 years old. It is made of banana, lemon juice, dried non-fat milk, white canned beans, and dried mushrooms. The snack is designed to provide a controlled amount of energy, iron, calcium, and vitamin D required for children at these age levels. It is produced through an extrusion-based printing technology. Pectin was found to be useful in this application as it enabled the 3D printing of puree, which is a gelling agent commonly used in the food industry. Using such food material to be combined in the pre-extrusion phase resulted in good printing quality [18].

4.4 Prospects

3D printing of food still has a lot of room for growth in terms of maintenance, scale of production, and the quality of the manufactured food. In order to increase printability of food, thickening agents such as starch and gelatin can be used. Food 3D printers have printing systems which often result in laborious maintenance which require them to be manually and carefully cleaned. This could be aided by some sort of automated cleaning system within the 3D printer. For food materials that can be directly printed, future research can show feasible food that can also be made through additive manufacturing. [23].

Table 2. Applications, Materials, and 3D Printing Techniques Used for Additive Manufacturing in Food.

3D Printed Food	Application	Material/Filament	3D Printing Technique	Reference
Cake	Rapid Manufacturing	Frosting	Extrusion-based 3D printing	[32]
Meat Slurry	Increase food intake	Gelatin and meat	Extrusion-based 3D printing	[23]
Vegetables	Increase food intake	Carrots, peas, and corn	Extrusion-based 3D printing	[19]
Fruit-based snack	Personalized Nutrition	Banana, lemon juice, etc.	Extrusion-based 3D printing	[18]
Pizza	Rapid Manufacturing	Dough and tomato sauce	Extrusion-based 3D printing	[34]
Pasta	Rapid Manufacturing	Traditional pasta	Extrusion-based 3D printing	[23]
Chocolate	Customized dessert	Chocolate	Extrusion-based 3D printing	[35]

5. 3D Printing Applications in Environment

5.1 Printing Technology and Materials

Selective laser sintering (SLS), Fused deposition modeling (FDM), and vertical 3D printing are the printing methods used for the fabrication of the parts of equipment and objects for the environmental applications of 3D printing. For the air quality monitoring device called "nEMos," thermoplastic in the form of PLA is used for its lightweight property, enabling the device to be carried anywhere for air quality testing [21]. The 3D printed biocarrier is made of nylon that has excellent mechanical properties and straightforward processing attribute [17]. This property of nylon helps significantly in wastewater management. Graphene is the material of choice for the 3D printed evaporator as it is known to have high molecular barrier ability [36]. The artificial coral reef is implied to be 3D printed out of limestone which is mainly composed of calcium carbonate ($CaCo_3$), the natural chemical compound present in naturally existing coral reefs. This material is practically insoluble in water and helps in building other blocks of the reef structure that provide food and shelter for life under water [37]. Other environmental applications of 3D printing include ceramic filters for water treatment [38], carbon anode for alternative energy sources [39], and fiber mesh for deicing [40]. Table 3 summarizes the application, material, and 3D printing techniques used for environmental applications.

5.2 Air quality monitoring

The 3D printed case shown in Figure 5 [21], houses the nano environmental monitoring system (nEMoS) device that is used for calculating the Indoor Environmental Quality (IEQ), which is a measure of the air quality of the environment regarding the health and well-being of the occupants in a particular place. The case is made out of PLA thermoplastic that requires less energy to be produced and is sourced out of renewable resources such as corn starch, making it one of the most sustainable materials in the market [21].

Figure 5. 3D printed case for nEMos [21]

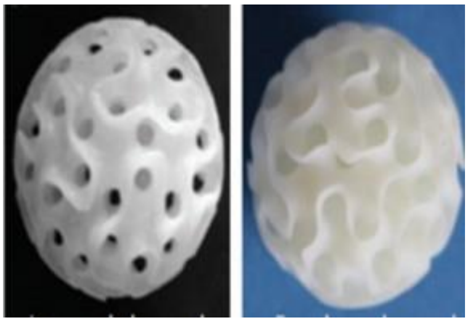

Figure 6. 3D printed biocarriers [14]

5.3 Water Treatment

As previously reported by Tijing et al., 3d printing may be used in water desalination, membrane separation and water purification applications [36]. 3D-printed solar absorbers using the solar-driven interfacial water evaporation (SWE) to produce clean water has also been reported by their group [15]. The 3D printed bio-carriers modelled to the microstructure of fullerene, as shown in Figure 6 [14], aims to improve general performance and organic matter removal of biofilm reactors through specialized structures. It is manufactured through the SLS 3D printing technology. The material used to manufacture this device is a specific type of nylon that is easy to process. 3d printing allows more freedom in the design of the device's structure than in the manufacturing of commercially available bio-carriers.

3D printing presents a possible solution for shortage of clean water through desalination using a 3D printed jellyfish-like evaporator. It is manufactured using vertical 3D printing technology. Its material is composed of graphene which has remarkable properties such as high electrical conductivity and mechanical strength, in this case the most relevant being the material's high molecular barrier abilities. 3D printing allows prototyping and fabrication of photothermal materials such as graphene with desirable properties for solar steam evaporation (SSE) and with designed architecture. [37]

5.4 Artificial Habitat

The artificial coral reef is created by the company XtreeE for synthetic habitat of aquatic life. It is manufactured using a large-scale industrial printer that employs fused deposition modeling, with the material having biomimetic and porous properties resembling the coral itself. 3D printing allows the immediate replacement of coral reefs which can be susceptible to disintegration due to many undesirable aquatic factors such as the warming of the oceans that leads to the proliferation of carbon dioxide in the water, consequently endangering the survival of coral reefs due to acidification [38]

5.5 Prospects

As far as sustainable manufacturing is concerned, 3D printing is top-notch. However, the efficiency of 3D printing systems and the scaling-up of the printing process are still subject to improvement. Prospective materials with desirable properties are yet to be considered in future research. As for well-established materials for 3D printing, printing resolution and accuracy can also be made advanced through further research. [37]

Table 2. Applications, Materials, and 3D Printing Techniques Used for Additive Manufacturing for the Environment

3D Printed Object	Application	Material/Filament	3D Printing Technique	Reference
Case	Air quality monitoring	PLA	Fused deposition modeling	[21]
Bio-carrier	Water treatment	Nylon	Selective laser sintering	[37]

Evaporator	Water treatment	Graphene	Vertical 3D printing	[37]
Coral reef	Artificial habitat	Limestone	Fused deposition modeling	[38]
Clay ceramic	Water treatment	Clay	Extrusion-based 3D Printing	[39]
Anode	Energy source	Carbon	3D printing	[40]
Mesh	Turbine deicing	Carbon fiber	Extrusion-based 3D printing	[41]

6. Conclusion

3D printing is now being widely used in various applications. From manual labor to the creation of machines that help us manufacture the products that we consume and the things that have practical applications, additive manufacturing enables the creation of these as we channel our ideas from the digital to the tangible. With this technology, we can save time and capital which would otherwise be allocated with the conventional methods of manufacturing that often go through lengthy and convoluted processes. It helps us adhere to sustainable and efficient manufacturing as it constantly finds useful applications in many different industries and fields. This paper presented some use cases of 3D printing in the fields of agriculture, food processing, and environment protection and monitoring. Specifically, the paper discussed the different materials used in 3D printing of parts, the different printing technologies employed.

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