Additive Manufacturing

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Additive manufacturing, which is also known as 3D printing, is an emerging and growing technology. It is providing significant innovations and improvements in many areas such as engineering, production, medicine, and more. 3D food printing is an area of great promise to provide an indulgence or entertaining experience, personalized food product, or specific nutritional needs. This entry reviews the additive manufacturing methods and materials in detail as well as their advantages and disadvantages. After a full discussion of 3D food printing, the reports on edible printed materials are briefly presented and discussed. In the end, the current and future outlook of additive manufacturing in the food industry is shown.

Keywords: additive manufacturing ; 3D food printing ; formulation ; natural polymers ; extrusion ; material ; customized food ; hydrocolloids ; jetting ; edible

1. Introduction

The term "additive manufacturing (AM)", which is often termed 3D printing and rapid prototyping, covers several quite different manufacturing technologies that enable the creation of objects to be fabricated on demand[1][2]. The basic concept of AM is a controlled process whereby a product is built up from a digital design (usually a Computer-Aided Design (CAD) file)[3][4]. While printing the object, the 3D model is sliced into layers, by the software, and then printed one at a time (layer by layer)[5]. AM has emerged as one of the most disruptive manufacturing technologies and, consequently, has significant implications for companies and industries[6]. The adoption of these technologies comprises four successive stages: rapid prototyping, rapid tooling, digital manufacturing, and home fabrication[5]. Each stage corresponds to a different degree of involvement of 3D printing in the manufacturing process. By using a business model, Rayna and Striukova[5] have concluded that rapid prototyping and rapid tooling had a limited impact, but direct manufacturing and home fabrication can be highly disruptive[5].

The advantages of AM, in general, are low waste, increased precision, time-saving, and high efficiency[7]. AM is a platform that enables the manufacture of complex structures from digital design data immediately, without special tools and equipment, by providing new opportunities for freedom of design[8]. Rapid prototyping is one of the main benefits of 3D printing[9]. AM offers the capacity to build objects with any shape and dimension as well as the ability to control chemical, physical, mechanical properties, and an internal structure (microstructure) by modifying their composition[10][11].

AM is a mass-customisation and personalisation-enabling technology[6]. Due to limits in production speed among other technological bottlenecks, 3D printing is ideal for mass customisation but is not yet capable of mass production[6][12]. AM enables private and commercial users to design and create their products simply and quickly, especially for low volume, customised, high-value products[8][13]. Most equipment used in AM can be used to produce a variety of different parts at nearly any location by potentially allowing decentralisation and localisation of production for companies[6].

Therefore, AM offers opportunities for advancement in remote areas with low economic profiles by bridging the gap between these areas and the next market, and by supplying these areas with the necessary objects to improve quality of life[13]. AM significantly lowers labour demands as well as financial and energy resource inputs into manufacturing processes, which leads to a decrease in production costs and CO_2 emissions[13]. The layer-by-layer nature of production, specifically the ability to lower product infill, greatly lowers resource demands and process-related waste[13]. Conventionally, one-of-a-kind manufacturing is associated with surplus material being wasted[8]. However, with AM technologies, highly customised products can be manufactured more sustainably[1]. By using 3D printing, it could be possible to develop a local material recycling and manufacturing loop, which translates into reductions in landfill and emissions, and leads to an increase in local employment through recycling centres as well as value creation[14].

In its early days, AM was used for rapid prototyping and then tooling and these application areas continue to be used[1]. There is an abundance of evidence that suggests AM will be promising in the following areas[15][16]: (1) customised healthcare products for improving health and quality of life. There are several reports on amenable 3D printing technologies for pharmaceutical manufacturing[17][18], which are applicable to different drug development phases (early-phase screening, testing, manufacturing, and dispensing)[19]. Human medicine, as well as veterinary medicine, can benefit from technological advances in 3D printing[20][21][22][23][24]. 3D printing is important to dentistry and can be used to print personalised braces for patients[25][26]. Surgeons have also reported the application of 3D printing in their respective subspecialties[27][28][29]. (2) Other evidence that shows AM is promising includes reduced environmental impact by increasing manufacturing sustainability. In the construction industry, many experiments have been conducted to explore the full potential of 3D printing as a core method to build more sustainable and environmentally-friendly buildings, or to produce construction components[30]. Considerable research is ongoing to use wood and forest products as 3D printing feedstock to impart texture to the surface of the printed products and meet the demand for sustainability from consumers[12]. (3) The third piece of evidence is supply chain simplification to increase efficiency and responsiveness. The various AM technologies that enable the development of fashion products like apparel and jewelry are closely associated with low-volume manufacturing and mass customization[31].

Additive manufacturing has been labelled a “disruptive technology” because it will fundamentally affect many processes in production, supply chain design, logistics, product life-cycle planning, and consumer behavior [8]. Due to the performance improvements of AM technologies, they are seeing increased usage in direct manufacturing rather than being classified as a ‘technique for prototyping’[10]. For example, 3D printers are being utilised in analytical laboratories in a wide array of applications[32]. Moreover, the societal impact study from a technical perspective shows further research is necessary in life-cycle energy consumption evaluation and potential occupation hazard assessment for additive manufacturing[15].

One of the more challenging and complex areas of AM are in the emerging field of gastronomy, or in other words, “3D Food printing” [4]. The ability to selectively deposit material within a 3D volume and, hence, gradate the composition offers the possibility of controlled production of complex structures for altering texture, taste, and morphology in food products. Manipulation of microstructures by regulating the mixing and selective deposition of materials can allow regulation of fracture, breakdown, or dissolution mechanics during product use, which gives the possibility of a range of functional and novel foods.

In the past few years, several reviews highlighted different aspects of 3D Food printing[33]. For example, an overview of current research in printable food formulations[34][35], the review of 3D printing techniques applied to design food materials[36][37], the potential legal challenges and environmental implications of 3D Food printing[38], a review on existing food 3D printers alongside their advantages/disadvantages[39], and a review on 3D model design, model building, and model slicing in 3D Food printing[40]. However, the field of printable food materials has been growing, and, therefore, there is a need to collate and categorise published reports and to consolidate these developments. As such, we can have a better understanding of the accomplishments to date, and potential areas for future studies.

2. Additive Manufacturing: Material and Methods

Various 3D printing processes have been reported to date[41]. A summarised timeline of the history of AM can be found in Jakus (2019)[42]. The American Society of Testing and Materials (ASTM F2792-12a) have categorised the existing technologies under the following seven headings: (1) Vat photo-polymerization, (2) material extrusion, (3) directed energy deposition, (4) powder bed fusion, (5) binder jetting, (6) material jetting, and (7) sheet lamination[41][43]. These can be further categorised by the characteristics of the printed medium (liquid-, solid-, and powder-based materials) and, by the process, used to fuse matter on a molecular scale (thermal, UV-light, laser, or electron beam)[13]. To differentiate themselves, various manufacturers often use different acronyms for describing the same process, and, therefore, similar techniques might have different names[43]. These have all been previously compared and reviewed comprehensively[17][44][45][46], and many of these techniques have been individually reviewed in high detail including powder-based electron beam additive manufacturing (EBAM) technology[47], and the Fused Filament Fabrication (FFF) process, also termed, Fused Deposition Modelling (FDM)[48][49].

Materials have long been a barrier to the broader uptake of AM in the manufacturing industry[50]. There are several comprehensive reviews of 3D printing techniques in terms of the materials utilised among them[9][45][51][52][53][54][55]. The material selection depends on the process and the physical state of the material[13] as well as on the phase transitions or chemical reactions to bind the layers together[56][57]. The basic materials in 3D printing include a wide range of plastics such as commonly used acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and nylon. A handful of other materials, for example, cellulose plus its derivatives[58] and hydrogels[59], are also well established in AM and well accepted in some manufacturing applications. However, not many have reached the stage of full commercialisation.

Further progress in 3D printing will require the concurrent development of pioneering 3D printing methods in addition to novel feedstocks of material suitable for the devised processing methods[51].

References

1. Ford, S.; Despeisse, M. Additive manufacturing and sustainability: An exploratory study of the advantages and challenges. J. Clean. Prod. 2016, 137, 1573–1587.
2. Severini, C.; Derossi, A.; Azzollini, D. Variables affecting the printability of foods: Preliminary tests on cereal-based products. Innov. Food Sci. Emerg. Technol. 2016, 38, 281–291.
3. Izdebska, J.; Zołek-Tryznowska, Z. 3D food printing—Facts and future. Agro Food Ind. Hi Tech 2016, 27, 33–37.
4. Dankar, I.; Haddarah, A.; Omar, F.E.L.; Sepulcre, F.; Pujolà, M. 3D printing technology: The new era for food customization and elaboration. Trends Food Sci. Technol. 2018, 75, 231–242.
5. Thierry Rayna; Ludmila Striukova; From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change* **2016**, *102*, 214-224, 10.1016/j.techfore.2015.07.023.
6. Marcel Bogers; Ronen Hadar; Arne Bilberg; Additive manufacturing for consumer-centric business models: Implications for supply chains in consumer goods manufacturing. *Technological Forecasting and Social Change* **2016**, *102*, 225-239, 10.1016/j.techfore.2015.07.024.
7. Jingwang Chen; Mu Tai-Hua; Dorothée Goffin; Christophe Blecker; Gaëtan Richard; Aurore Richel; Eric Haubruge; Application of soy protein isolate and hydrocolloids based mixtures as promising food material in 3D food printing. *Journal of Food Engineering* **2019**, *261*, 76-86, 10.1016/j.jfoodeng.2019.03.016.
8. Ruth Jiang; Robin Kleer; Frank T. Piller; Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030. *Technological Forecasting and Social Change* **2017**, *117*, 84-97, 10.1016/j.techfore.2017.01.006.
9. Tuan D. Ngo; Alireza Kashani; Gabriele Imbalzano; Kate T.Q. Nguyen; David Hui; Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering* **2018**, *143*, 172-196, 10.1016/j.compositesb.2018.02.012.
10. Poologasundarampillai, G.; Nommeots-Nomm, A. Materials for 3D Printing in Medicine: Metals, Polymers, Ceramics, Hydrogels. In 3D Printing in Medicine; Woodhead Publishing: Sawston/Cambridge, UK, 2017; pp. 43–71. ISBN 9780081007266.
11. Severini, C.; Derossi, A.; Ricci, I.; Caporizzi, R.; Fiore, A. Printing a blend of fruit and vegetables. New advances on critical variables and shelf life of 3D edible objects. J. Food Eng. 2018, 220, 89–100.
12. Li, T.J.; Aspler, J.; Kingsland, A.; Cormier, L.M.; Zou, X.J.; 3D Printing—A Review of Technologies, Markets, and Opportunities for the Forest Industry. *J. Sci. Technol. For. Prod. Process.* **2015**, *5*, 60–67, .
13. Malte Gebler; Anton J.M. Schoot Uiterkamp; Cindy Visser; A global sustainability perspective on 3D printing technologies. *Energy Policy* **2014**, *74*, 158-167, 10.1016/j.enpol.2014.08.033.
14. Alysia Garmulewicz; Matthias Holweg; Hans Veldhuis; Aidong Yang; Disruptive Technology as an Enabler of the Circular Economy: What Potential Does 3D Printing Hold?. *California Management Review* **2018**, *60*, 112-132, 10.1177/0008125617752695.
15. Huang, S.H.; Liu, P.; Mokasdar, A.; Hou, L. Additive manufacturing and its societal impact: A literature review. Int. J. Adv. Manuf. Technol. 2013, 67, 1191–1203.
16. Baumers, M.; Dickens, P.; Tuck, C.; Hague, R. The cost of additive manufacturing: Machine productivity, economies of scale and technology-push. Technol. Forecast. Soc. Chang. 2016, 102, 193–201.
17. Rahman, Z.; Barakh Ali, S.F.; Ozkan, T.; Charoo, N.A.; Reddy, I.K.; Khan, M.A. Additive Manufacturing with 3D Printing: Progress from Bench to Bedside. AAPS J. 2018, 20, 101.
18. Prasad, L.K.; Smyth, H. 3D Printing technologies for drug delivery: A review. Drug Dev. Ind. Pharm. 2016, 42, 1019–1031.
19. Atheer Awad; Sarah J. Trenfield; Alvaro Goyanes; Simon Gaisford; Abdul W. Basit; Reshaping drug development using 3D printing. *Drug Discovery Today* **2018**, *23*, 1547-1555, 10.1016/j.drudis.2018.05.025.
20. Hespel, A.-M.; Wilhite, R.; Hudson, J. Invited Review-Applications for 3D Printers in Veterinary Medicine. Vet. Radiol. Ultrasound 2014, 55, 347–358.

21. Zhuang, Y.; Zhou, M.; Liu, S.; Wu, J.; Wang, R.; Chen, C. Effectiveness of personalized 3D printed models for patient education in degenerative lumbar disease. Patient Educ. Couns. 2019, 102, 1875–1881.

22. Velázquez, J.S.; Cavas, F.; Bolarín, J.M.; Alió, J.L. 3D printed personalized corneal models as a tool for improving patient’s knowledge of an asymmetric disease. Symmetry 2020, 12, 151.

23. Panesar, S.S.; Magnetta, M.; Mukherjee, D.; Abhinav, K.; Branstetter, B.F.; Gardner, P.A.; Iv, M.; Fernandez-Miranda, J.C. Patient-specific 3-dimensionally printed models for neurosurgical planning and education. Neurosurg. Focus 2019, 47, E12.

24. Tanner, J.A.; Jethwa, B.; Jackson, J.; Bartanuszova, M.; King, T.S.; Bhattacharya, A.; Sharma, R. A Three-Dimensional Print Model of the Pterygopalatine Fossa Significantly Enhances the Learning Experience. Anat. Sci. Educ. 2020, 13, 1–13.

25. Dawood, A.; Marti, B.M.; Sauret-Jackson, V.; Darwood, A. 3D printing in dentistry. Br. Dent. J. 2015, 219, 521–529.

26. Lin, L.; Fang, Y.; Liao, Y.; Chen, G.; Gao, C.; Zhu, P. 3D Printing and Digital Processing Techniques in Dentistry: A Review of Literature. Adv. Eng. Mater. 2019, 21, 1801013.

27. DiPaola, M.; Wodajo, F.M. Building the Future of Orthopedics: One Layer at a Time. In 3D Printing in Orthopaedic Surgery; Elsevier: Amsterdam, The Netherlands, 2018.

28. Malik, H.H.; Darwood, A.R.J.; Shaunak, S.; Kulatilake, P.; El-Hilly, A.A.; Mulki, O.; Baskaradas, A. Three-dimensional printing in surgery: A review of current surgical applications. J. Surg. Res. 2015, 199, 512–522.

29. Chae, M.P.; Rozen, W.M.; McMenamin, P.G.; Findlay, M.W.; Spychal, R.T.; Hunter-Smith, D.J. Emerging Applications of Bedside 3D Printing in Plastic Surgery. Front. Surg. 2015, 2, 1–14.

30. Peng Wu; Jun Wang; Xiangyu Wang; A critical review of the use of 3-D printing in the construction industry. *Automation in Construction* **2016**, *68*, 21-31, 10.1016/j.autcon.2016.04.005.

31. Y.L. Yap; Wai Yee Yeong; Additive manufacture of fashion and jewellery products: a mini review. *Virtual and Physical Prototyping* **2014**, *9*, 195-201, 10.1080/17452759.2014.938993.

32. Bethany Gross; Sarah Y. Lockwood; Dana M. Spence; Recent Advances in Analytical Chemistry by 3D Printing. *Analytical Chemistry* **2016**, *89*, 57-70, 10.1021/acs.analchem.6b04344.

33. Fundamentals of 3D Food Printing and Applications; Godoi, F.C.; Bhandari, B.R.; Prakash, S.; Zhang, M. (Eds.) Elsevier Inc.: Amsterdam, The Netherlands, 2019.

34. Voon, S.L.; An, J.; Wong, G.; Zhang, Y.; Chua, C.K. 3D food printing: A categorised review of inks and their development. Virtual Phys. Prototyp. 2019, 14, 203–218.

35. Jiang, H.; Zheng, L.; Zou, Y.; Tong, Z.; Han, S.; Wang, S. 3D food printing: Main components selection by considering rheological properties. Crit. Rev. Food Sci. Nutr. 2019, 59, 2335–2347.

36. Godoi, F.C.; Prakash, S.; Bhandari, B.R. 3D printing technologies applied for food design: Status and prospects. J. Food Eng. 2016, 179, 44–54.

37. Sun, J.; Zhou, W.; Huang, D.; Fuh, J.Y.H.; Hong, G.S. An Overview of 3D Printing Technologies for Food Fabrication. Food Bioprocess Technol. 2015, 8, 1605–1615.

38. Jasper Tran; 3D-Printed Food. *Minnesota J. Law Sci. Technol.* **2016**, *17*, 855, 10.17605/osf.io/qsfvh.

39. Toh, W.Y.; Li, L.; Chua, C.K. Comparison of Existing 3D Food Printers. In Proceedings of the 3rd International Conference on Progress in Additive Manufacturing (Pro-AM 2018), Singapore, 14–17 May 2018; Chua, C.K., Yeong, W.Y., Tan, M.J., Liu, E., Tor, S.B., Eds.; Nanyang Technological University: Singapore, 2018.

40. Chao-Fan Guo; Min Zhang; Bhesh Bhandari; Model Building and Slicing in Food 3D Printing Processes: A Review. *Comprehensive Reviews in Food Science and Food Safety* **2019**, *18*, 1052-1069, 10.1111/1541-4337.12443.

41. Mohammad Vaezi; Srisit Chianrabutra; Brian Mellor; Shoufeng Yang; Multiple material additive manufacturing – Part 1: a review. *Virtual and Physical Prototyping* **2013**, *8*, 19-50, 10.1080/17452759.2013.778175.

42. Jakus, A.E. An Introduction to 3D Printing—Past, Present, and Future Promise. In 3D Printing in Orthopaedic Surgery; Elsevier Inc.: Amsterdam, The Netherlands, 2018; pp. 1–15. ISBN 9780323581189.

43. Saptarshi, S.M.; Zhou, D.C. Basics of 3D Printing. In 3D Printing in Orthopaedic Surgery; Elsevier: Amsterdam, The Netherlands, 2019; pp. 17–30. ISBN 9780323581189.

44. Ligon, S.C.; Liska, R.; Stampfl, J.; Gurr, M.; Mülhaupt, R. Polymers for 3D Printing and Customized Additive Manufacturing. Chem. Rev. 2017, 117, 10212–10290.

45. Hegab, H.A. Design for additive manufacturing of composite materials and potential alloys: A review. Manuf. Rev. 2016, 3, 11.

46. Bikas, H.; Stavropoulos, P.; Chryssolouris, G. Additive manufacturing methods and modeling approaches: A critical review. Int. J. Adv. Manuf. Technol. 2016, 83, 389–405.

47. Gong, X.; Anderson, T.; Chou, K. Review on Powder-Based Electron Beam Additive Manufacturing Technology. In Proceedings of the ASME/ISCIE 2012 International Symposium on Flexible Automation, St. Louis, MI, USA, 18–20 June 2012; p. 507

48. Brenken, B.; Barocio, E.; Favaloro, A.; Kunc, V.; Pipes, R.B. Fused filament fabrication of fiber-reinforced polymers: A review. Addit. Manuf. 2018, 21, 1–16.

49. Salentijn, G.I.J.; Oomen, P.E.; Grajewski, M.; Verpoorte, E. Fused Deposition Modeling 3D Printing for (Bio)analytical Device Fabrication: Procedures, Materials, and Applications. Anal. Chem. 2017, 89, 7053–7061.

50. Chee Kai Chua; Wai Yee Yeong; Jia An; Special Issue: NextGen Materials for 3D Printing. *Materials* **2018**, *11*, 555, 10.3390/ma11040555.

51. Chang, J.; He, J.; Mao, M.; Zhou, W.; Lei, Q.; Li, X.; Li, D.; Chua, C.K.; Zhao, X. Advanced material strategies for next-generation additive manufacturing. Materials 2018, 11, 166.

52. Singh, S.; Ramakrishna, S.; Singh, R. Material issues in additive manufacturing: A review. J. Manuf. Process. 2017, 25, 185–200.

53. Zolfagharian, A.; Kouzani, A.Z.; Khoo, S.Y.; Gibson, I.; Kaynak, A. 3D Printed Hydrogel Soft Actuators. In Proceedings of the IEEE Region 10 Annual International Conference Proceedings/TENCON, George Town, Malaysia, 5–8 November 2017; pp. 2272–2277.

54. Bourell, D.; Kruth, J.P.; Leu, M.; Levy, G.; Rosen, D.; Beese, A.M.; Clare, A. Materials for additive manufacturing. CIRP Ann.-Manuf. Technol. 2017, 66, 659–681.

55. Utela, B.; Storti, D.; Anderson, R.; Ganter, M. A review of process development steps for new material systems in three dimensional printing (3DP). J. Manuf. Process. 2008, 10, 96–104.

56. Liu, Y.; Liu, D.; Wei, G.; Ma, Y.; Bhandari, B.; Zhou, P. 3D printed milk protein food simulant: Improving the printing performance of milk protein concentration by incorporating whey protein isolate. Innov. Food Sci. Emerg. Technol. 2018, 49, 116–126.

57. Portanguen, S.; Tournayre, P.; Sicard, J.; Astruc, T.; Mirade, P.S. Toward the design of functional foods and biobased products by 3D printing: A review. Trends Food Sci. Technol. 2019, 86, 188–198.

58. Lei Dai; Ting Cheng; Chao Duan; Wei Zhao; Weipeng Zhang; Xuejun Zou; Joseph Aspler; Yonghao Ni; 3D printing using plant-derived cellulose and its derivatives: A review. *Carbohydrate Polymers* **2019**, *203*, 71-86, 10.1016/j.carbpol.2018.09.027.

59. Huijun Li; Cavin Tan; Lin Li; Review of 3D printable hydrogels and constructs. *Materials & Design* **2018**, *159*, 20-38, 10.1016/j.matdes.2018.08.023.
