A Versatile Journey: From Plastic Prototyping to Food Printing

S. Hermanová[1*], Š. Nedomová[2], A. Roztočilová[2*]

[1] University of Pardubice, Studentska 95, 532 10 Pardubice 2, Czech Republic

[2] Department of Food Technology, Faculty of AgriSciences, Mendel University in Brno, Zemedelska 1, 613 00 Brno, Czech Republic

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ABSTRACT

3D printing, also known as additive manufacturing, is an innovative technology that has revolutionized various industries. The benefits of 3D food printing include the ability to produce novel textures, customized shapes, and complex geometries, offering new possibilities in culinary arts and confectionery production. This approach enhances aesthetic appeal and allows for personalized and unique edible creations, pushing the boundaries of traditional food manufacturing. This study explores the innovative process of 3D food printing, leveraging the foundational techniques of 3D plastic prototyping. Initially, prototypes were developed using a 3D plastic printer to refine design and structural integrity. Subsequently, these prototypes were adapted for use with a 3D food printer, enabling the creation of specific food designs. We believe that combining 3D printing technology and food matrices with customized composition can satisfy consumer demands, dietary preferences, and potential health restrictions. In addition to its research applications, the concept can be integrated into technology teacher education at universities. Consequently, digital modelling and 3D printing knowledge provide students with essential 21st-century digital skills.

[*]Corresponding authors: sona.hermanova@upce.cz, andrea.roztocilova@mendelu.cz

INTRODUCTION

3D food printing is an additive manufacturing technology that enables the creation of complex, 3D-designed objects through the layer-by-layer deposition of food materials (Nachal et al. 2019). Nowadays, four basic techniques of 3D printing have been applied in the food sector including extrusion-based 3D printing, binder jetting, inkjet printing, and selective laser sintering (Kewuyemi, Hema, and and Adebo 2022). Among 3D printing techniques, hot and cold extrusion-based 3D printing attracted huge attention due to accessibility of commercial 3D food printers and printability of various food matrices (Outrequin et al. 2023). For extrusion printing, food filament or strand is deposited on the built plate through the printer's nozzle by a screw, a piston, or a pneumatic system while the head movement is coordinated in accordance with computer-aided design (CAD) 3D model (Sun et al. 2018). Principally, 2D patterns are repeatedly deposited on a built plate, stacking and forming a solid 3D object through phase transition or cross-linking (Yan et al. 2022).

Food matrices suitable for 3D food printing using cold extrusion (room temperature) include cereal-based substrates, protein gels, and dairy-based products with additives such as lipids, hydrocolloids, and carbohydrates to achieve enhanced rheological properties (Chen et al. 2022). Hot melt extrusion 3D printing is widely utilized for chocolate products manufacturing. Recently the effect of rheological and thermal transition properties of starchy food materials on the feasibility of hot extrusion 3D printing has been studied (Zhang et al. 2022).

Despite the popularity of chocolate as a commodity for 3D printing, it is not easy to work with due to its complex composition and rheological properties including shear thinning and thixotropic behaviour (VA et al. 2023). Typical ingredients including cocoa mass, sugar, emulsifier, and in case of milk chocolate also milk, powder possess varying thermal properties which can impact flow properties of chocolate during the extrusion (Konar et al. 2024). The effect of additives like magnesium stearate and plant sterol on the thermal, rheological, and tribological properties of 3D printed dark chocolate was studied to achieve improved flow behaviour for the extrusion (Mantihal et al. 2019). You *et al* successfully developed 3D printed chocolate by substituting some part of cocoa butter with Arabic gum-based water-in-oil emulsions (You, Huang, and Lu 2023).

Moreover, 3D printing technology has offered the possibility to prepare customized products for the chocolate market according to special diet demands including options with reduced sugar content or bioactive agents' enrichment (Karavasili et al., 2020; Khemacheevakul et al., 2021). Chocolate with reduced sugar content was obtained by substitution of sugar with carob extract (30% ratio) (Cikrikci Erunsal et al. 2023). To conclude, chocolate belongs to convenient representatives of food matrices with partially tailorable composition and capability to be processed by extrusion-based 3D printing. This study highlights primary printing parameters affecting the resulting texture of 3D-printed edible objects, emphasizing chocolate 3D printing.

Primary printing parameters

The infill density (percentage) and infill pattern represent two critical parameters to be precisely designed to ensure structural integrity of 3D printed object (Liu et al. 2018). To minimize material consumption while achieving acceptable structural stability, a balanced infill percentage is typically chosen at the beginning of objects' production. The effect of infill parameters on the textural properties of Cadbury dark chocolate was studied by the research team from The University of Queensland (Mantihal, Prakash, and Bhandari 2019). Chocolate objects with star and honeycomb infill patterns showed enhanced mechanical property as compared to those with Hilbert curve pattern due to crosswise infilling structure. In the following study, sensory evaluation performed by 30 semi-trained panellists suggested potential consumers' preferences for 3D chocolate samples with 25% infill percentage particularly in terms of textural properties, when compared to samples with 50% and 100% infill percentages (M., B., and S. 2020). It is worth mentioning that the addition of certain internal support (cross direction) to 3D printed hexagonally shaped objects contributed to an enhancement of both the object stability and snap quality.

The importance of optimal nozzle height and layer height was emphasized by the study on 3D printed oleogels-enriched white chocolate for an achievement of precise geometry (Huang et al. 2023). Nozzle height is the distance from the nozzle tip to the top layer deposited on the built plate. Performed studies suggested that the optimal printing performance was achieved for the same values of nozzle height and nozzle diameter (Yang et al. 2018; M., B., and S. 2020).

Among other essential printing parameters are the printing temperature and printing speed. Regarding printing temperature, in hot-melt extrusion-based 3D printing, it was maintained in the 32 – 35 °C range for most chocolates studied, whereas cold extrusion of milk and dark chocolates was performed at 28 °C (VA et al. 2023). Printing speed and extrusion rate should be optimized according to nozzle diameter, nozzle, and layer height, since lower values can result in discontinuous lines, whereas higher values may affect geometry accuracy. Printing speed was reported from 5 to 70 mm·s^{-1} for most studied chocolates (VA et al. 2023).

Object modelling and prototyping

Commercially available 3D food printers offer a rich gallery of versatile-shaped templates from simple geometries to more complex or event-related forms. Users can select among various food templates, adjusting the object's size. Free *Thinkercad* software has been widely utilized to design personalized geometrical objects (Derossi et al. 2024). Created digital models are exported as STL formats, which can be sliced by food printer slicing software to subsequently generate printer-specific G-code. Based on our previous experience with object modelling and subsequent plastic prototypes production by a commercial 3D thermoplastic printer, the same approach was applied to produce objects of edible material composition with a 3D food printer. In our study, the original PRUSA mini 3D printer (Czech Republic) was used with PLA filament printing. The 3D printing enabled rapid production of various plastic prototypes, which served as a gallery of physical objects. The objects' gallery could be helpful in the evaluation of preliminary visual appearance and arrangement in packaging before the actual production of food objects, thereby preserving material consumption and reducing time demand. Representative pictures of objects printed according to templates created in *Thinkercad* are shown in **Figure 1**. Wall thickness of digital model was set at 2.0 mm, and it was obtained for PLA prototypes with hollow shapes. Chocolate 3D objects were also designed to have hollow shapes to observe structural stability better and printed by commercial 3D food printer Procusini 5.0 (Germany).

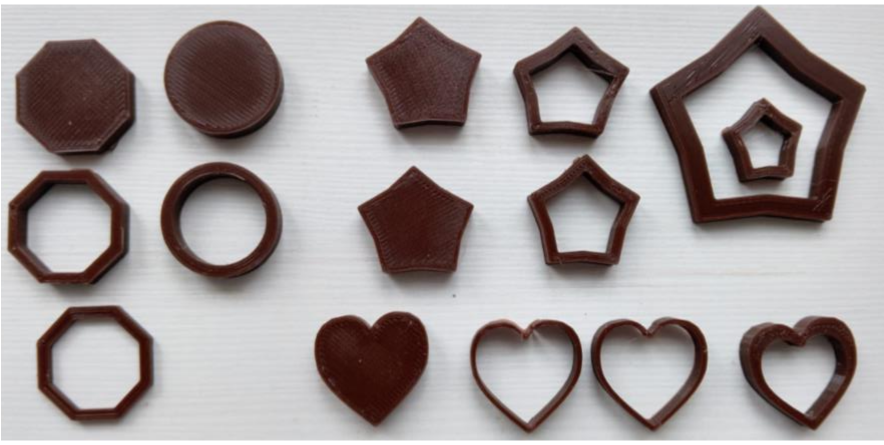

Figure 1 Representative PLA-based objects

Thanks to the economically acceptable prices of plastic 3D printers, they have been successfully introduced to university laboratories for project-based learning of students with the aim of supporting STEM education and digital skills enhancement (Ford and Minshall 2019). Similarly, 3D food printers can be integrated into both industrial and educational technology laboratories and pilot plants. By this approach a higher engagement of nutrition students in the courses if food science could be obtained (Gosine et al. 2021). In addition to its research application, 3D food printing can serve as a prospective education tool that enhances knowledge in the field of food sustainability and nutrition.

CONCLUSION

Our objective was to summarize important printing conditions that should be considered alongside 3D geometrical design to support the knowledge of food technologists and engineers in developing food products with new compositions and customized appearance for specific consumer groups. Successful 3D food printing requires multidisciplinary expertise in food science, nutrition, technology, and experience and understanding of printing conditions and model geometry design. Based on our concept, the synergistic use of knowledge in digital model designing and plastic prototype printing can subsequently facilitate the application in 3D food printing for a broad range of stakeholders.

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