Biopsychosocial Validation of 3D Food Printing

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Abstract

This study investigated how food additive manufacturing technology could be used to create a nutritional food product ("bar") with appropriate structural, nutritional, and visual properties. The research team developed a feedstock formulation for a three-layer bar and optimized printing parameters to produce high-quality prints. Both printing and post-processing parameters were modified to change the interior structure of the bar and, therefore, change the bar's texture. Mechanical testing was performed to determine the relationship between the texture and mechanical strength of the bar. The mechanical tests coupled with a consumer rating study (i.e., a taste test) with naïve human participants allowed for a viability evaluation. Aggregate results demonstrated that the bar is viable at certain ranges at each temperature interval. At 275°F, the only viable Young's modulus was 11.74×10^6 Pa. At 300°F, the viable range was between 1.26×10^6 to 16.3×10^6 Pa. At 325°F, the viable range was between 2.77×10^6 to 12.5×10^6 Pa. Lastly, at 350°F, the viable range was between 13.54×10^6 to 28.17×10^6 Pa. Overall, consumer satisfaction of the final iteration of the bar received an average of 5.0 on a scale of 1.0 to 6.0. Overall, these results support the suitability of our bar formulation and printing parameters for further development and scaling.

Meet the Team

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Table of Contents

List of Figures

List of Tables

Introduction

Three-dimensional food printing (3DFP) allows for the production of food products through a process involving various manufacturing techniques such as extrusion-based printing. This process has a number of potential applications, some of which are currently being researched. However, much of this research is restricted to only psychological or to only mechanical components without any integration. For instance, previous work has surveyed the public opinion of 3D printed food or investigated printing process optimization, but very few look at how human subjects respond to a specific 3D printed food product.

One possible application of 3D food printing is utilizing the technology to improve the nutrient and calorie intakes of members in the United States Armed Forces, also known as warfighters. The United States Armed Forces includes six military branches: Army, Air Force, Navy, Coast Guard, Marine Corps, and Space Force. The term "warfighter" therefore is used hereafter throughout this paper to be inclusive of all branches of the U.S Armed Forces, rather than using "soldier", which refers specifically to members of the Army. The United States military currently relies primarily on Meals Ready-to-Eat (MREs) to sustain its warfighters in the field. However, acceptance of MREs is low, especially over extended periods of time. One study found that after just three weeks of consuming MREs, warfighters would discard 40% of the meal [1]. This scale of food waste is not only fiscally inefficient, but also means warfighters are lacking in necessary nutrients and do not consume enough calories. A lack of proper nutrients and inadequate calorie-intake can lead to weight loss and decreased energy, as well as other health issues down the road.

With this in mind, this project aimed to advance the material science of 3DFP and integrate it with consumer rating studies, through developing a three layer nutritional, palatable 3D food printed bar. The base layer consisted primarily of oats and nuts. The middle layer consisted primarily of cinnamon applesauce and honey. The final layer consisted of a dark chocolate to add embellishment, similar to what is used on commercially available nutrition bars.

Background

3D Printing Food Overview

Three-dimensional food printing (3DFP), a type of additive manufacturing, is a revolutionary operation that provides new processing possibilities to the food industry. 3DFP is a process where structures are built layer-by-layer from a computational 3D model. Food inks (recipes) are added to an extruder, pushed out by an external source of power (air pressure unit), and then printed into a pre-designed shape [2]. The diagram in **Figure 1** represents crucial checkpoints in the 3D printing process.

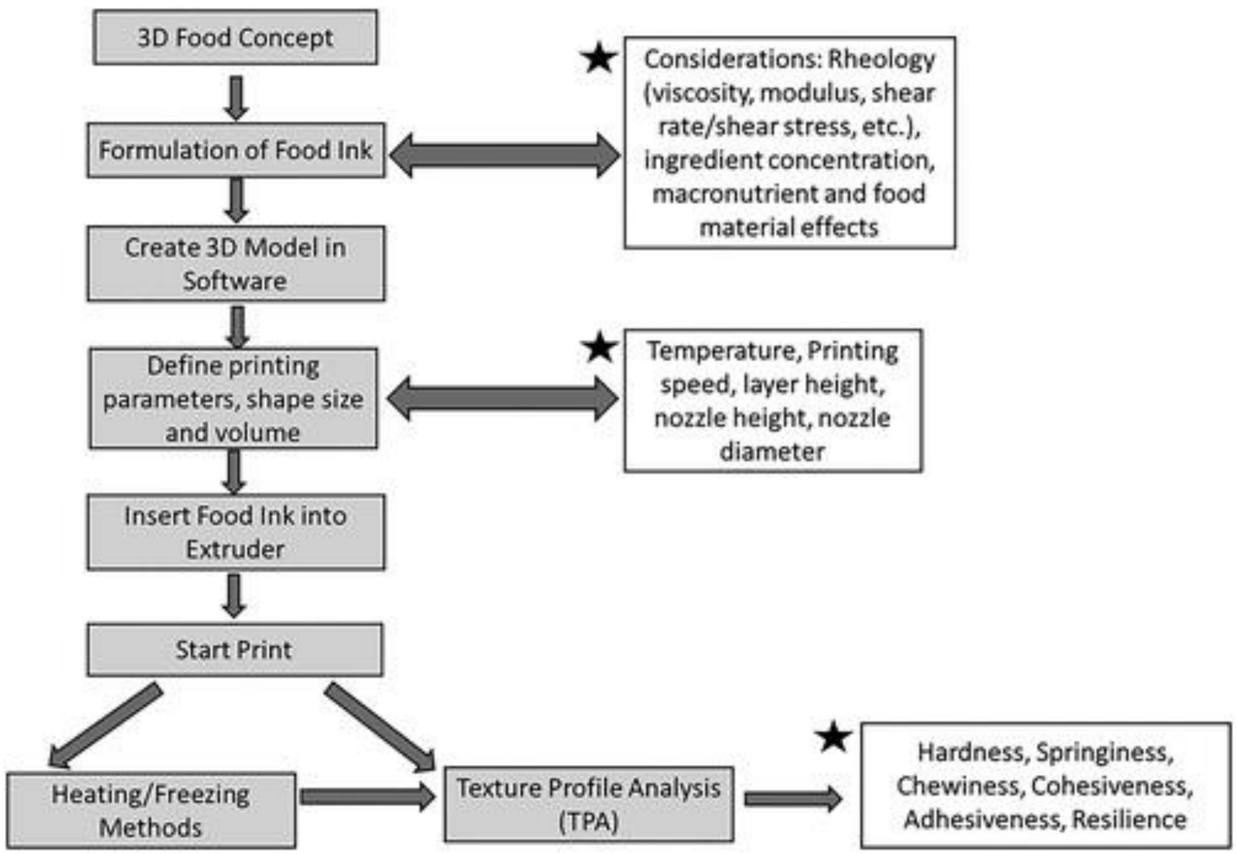


Figure 1. *Crucial checkpoints in the 3D printing process [2].*

Compared to other food manufacturing techniques, 3D food printing has several advantages. The first advantage is it can be easily customizable, unlike manufactured foods that are mass-produced. Everyone has different needs based on their personal taste, nutrition, and health, so 3DFP helps individuals print food to accommodate their needs. 3D food printing, offers "shape customization, personalization of nutrition, and the potential to modify the structure and texture of foods and precisely defined matter" [2]. 3DFP's ability to tailor food properties through design parameters for each individual allows the technology to have numerous potential applications in the food industry. Secondly, hand in hand with customizability, 3DFP reduces waste; because individuals are able to customize their food, they are only printing what they would consume. Manufactured foods tend to produce a great deal of waste because people either do not like the palate or buy more than they can consume. 3D food printing prints on demand so consumers can print as many times as they would like before they are satisfied. The last major advantage of 3DFP is the cost. 3DFP uses raw materials to produce a final product, avoiding the manufacturer. When food is 3D printed, there is no labor cost or shipping cost associated, and only the raw materials need to be bought. Overall, there are many advantages to 3DFP that make it a viable option for the future of the food industry.

Rheological Properties

It is extremely important to understand the rheological properties of food materials, as these properties influence printing performance. Rheology studies the flow of a food system under controlled conditions. These conditions include: viscosity, shear stress, shear rate, and yield stress. Viscosity measures a material's ability to resist force. Shear stress is defined as the force that causes deformation, and shear rate is the rate at which deformation is applied. Yield stress is defined as the maximum amount of force that can be applied to a material before deformation is irreversible. Printability results can be better estimated with an understanding of all the rheological properties listed above.

Printing Optimization

There are two main components to perfecting a 3D food printing process. The first main component is the optimization of the food matrix that is being printed. The second main component is taking food ink composition and rheology into consideration. This has to do with the design of the 3DFP process, which entails optimizing the printing parameters.

Formulation Optimization

Food inks are one of the most influencing factors in the success of 3D printing in the food industry. To achieve printability, the selected food ink is expected to be able to flow through a nozzle and set on the printing surface after it has been deposited. The macronutrient composition of material impacts the level of effectiveness of printing. Macronutrients provide the required physicochemical attributes to the food ink. The primary macronutrients include carbohydrates, proteins, and fats.

It should be noted that the composition of the food ink directly impacts the rheology of that food material, such as the viscosity [2]. As stated previously, rheological properties play a crucial role in the printability of a sample. Therefore, a lot of thought should go into the formula/food ink of a material to optimize the 3D food printing process.

Parameters Optimization

In addition to optimizing the formula of a material, one should also look into optimizing the printing parameters. The printing parameters of interest include temperature, printing speed, layer height, nozzle height, flow rate, and nozzle diameter [2]. The temperature of the system inversely affects the viscosity of a material. This means that at a higher temperature, the material becomes less viscous. Printing speed directly affects the structural stability of a material. At very fast printing speeds, layer formations are usually uneven, and the print is at low resolution. While at prolonged printing speeds, the structure of the print becomes unstable. Layer height directly affects the number of layers that can be produced. When the layer height is high, the material cannot hold its structural integrity, and when the layer height is low, it causes structural instability. Nozzle height also affects the resolution of the print. When the nozzle height is high, the placement of the materials is not accurate and therefore results in low resolution. When the nozzle height is low, the material is pressed into the surface of the plate, resulting in the material being laid outside the pre-designed path. Lastly, the nozzle diameter directly affects the printing precision. Larger nozzle diameters produce larger lines resulting in insufficient printing precision. However, larger food particles can fit through larger diameters. Smaller nozzle diameters will require more material than larger nozzle diameters, as the lines will be small, and more will be required to fill the same amount of space. The food ink has to have small particles with smaller nozzle sizes, or the nozzle will clog. Overall, both the formula and parameters need to be optimized to obtain successful printing results.

Main Challenges in 3D Food Printing

Although 3D food printing has the potential to make a real difference in the food industry, it is faced with many challenges. One of the main challenges 3PFP faces is customer acceptance [3]. Customers view new food technologies with suspicion. This suspicion arises from the concern of inefficient cleaning protocols and, therefore, potential health risks. The direct contact between the food ingredients and 3D printer parts is why customers are worried about microbiological decontamination. This form of contamination can lead to severe illnesses caused by bacteria, mold, and yeast. The best way to address this issue is to provide the consumers with all the facts. Author Antonietta Baiano states that while microbiological contamination and migration of toxic substances from printer elements is possible, there are "effective cleaning protocols and the use of materials authorized to come into contact with foods guarantee the necessary safety standards" [4]. It is important that customers know these cleaning protocols if the goal is to change their thoughts on 3DPF and increase acceptance. Other challenges include: the concern of the sustainability of 3D foods; the controversial ethical issues regarding 3D printing meat; and the unusual appearance of 3D foods.

Furthermore, it is going to take time until customers can accept 3DFP. It is relatively new to the food industry, and many kinks still have to be worked out. Still, the number of possible promising opportunities this novel food technology can offer is worth the time and research.

The Future of 3D Food Printing

Since 3D food printing is such a new field in the food industry, there has been limited success with real-world applications. In this section, future opportunities for 3DFP will be discussed. This method of food production will soon be able to produce food designs to meet the needs of each individual. Researcher Antonietta Baiano states that food printers will advance to a degree where individuals will be able to control their diet and calculate their exact calorie requirement "by selecting ingredient amount and type and the corresponding production parameters via an interface" [4]. 3D food printers will also be able to produce ready-to-eat foods for individuals with food-related diseases, such as diabetes or obesity, and individuals with personal eating habits, such as vegetarians.

Another exciting direction 3DFP can go is helping to increase the support system duration of a mission for NASA. The idea of developing 3D printed food systems for NASA has been discussed, and Baiano suggests that these foods can have a shelf life of several years which is excellent for long-duration space missions. These foods can also help minimize food waste as food will be customizable and extra material will not be needed.

Aside from these applications, 3DFP can help individuals who have problems chewing or swallowing. Individuals with these issues are restricted to a diet of only massed/pureed foods, which are usually unappealing and sometimes nutritionally inadequate [4]. 3DFP can model these mashed/pureed foods into more appealing shapes or even their original appearance. 3DFP can also customize the textures of the food so individuals will be more inclined to consume it.

Lastly, the ultimate goal for the future of 3D printing is to be able to print and post-process on a single machine. Achieving this goal will not be easy, as different food materials have different properties. Still, a device that could do both would be a significant technological advancement in the food industry. As of now, raw material is shaped in the desired 3D model in the 3D printer, then gets transported to a secondary location for post-processing (cooking, freezing, etc.).

Psychological Perspective of 3D Printed Food

Food Neophobia

Due to the limited studies on 3D food printing, further research on decreasing food neophobia, in general, was necessary. In a study by Okamoto et al. [5], researchers found that knowing what a food is before eating it increases the enjoyment of the food. They investigated this by giving participants one of four aqueous solutions. The solutions were flavored with either lemon, coffee jelly, consommé soup, and caramel candy. Half of the participants received a solution that was labeled with its flavor, and the other half received a solution labeled with a random 3-digit number. Participants were asked to judge the intensity and familiarity of the solution, as well as report how much they liked it. Results showed that participants who knew what the solution flavor was enjoyed it significantly more, especially when the flavor on the label seemed to match the taste of the solution [5]. These findings had several implications for the study. We decided to give a general description of the 3D printed bar we served participants to decrease their neophobia and make them enjoy the bar more. However, we had to be careful not to create any expectations with the description. If the description we gave did not match what the participant tasted, the lack of congruency would decrease the enjoyment of the food [5].

3D Printed Food Neophobia

As 3D food printing technology develops, further research is required to better understand the risks, benefits, and possibilities of this novel manufacturing process. However, with such a new technology, research on 3D printed food, that includes both consumer ratings and human subjects, has been extremely limited. Many studies were only able to survey general opinions [6,7], whereas others focus on the mechanical side of printing without a human subject component [8]. 3D food printing may be a great new method for food production, but the lack of information on societal acceptance of 3D food makes it hard to know if it is a viable option for the future. Fortunately, surveys on how 3D food is perceived generally find positive attitudes towards the technology [6, 7]. However, people tend to think of 3D printed food as a novelty or entertainment, rather than a source of sustenance. Words that have little to do with food like "futuristic," "innovative," and "visionary" were often used to describe it. Overall, past research has found that people are very interested in 3D food printing, but do not have a strong understanding of what it is [9].

One study conducted by Gayler & Kalnikaitē [6,7] aimed to assess how people either familiar or unfamiliar with 3D food printing felt about new food technology. Half of the participants belonged to a mailing list for a 3D printed food company, and the other half were computer science students. All participants completed three questionnaires. The first measured their general perception of new food technologies using the Food Neophobia Scale. The Food Neophobia Scale, also used in this study, assesses aversion to novel foods. The second questionnaire asked participants to consider the risks of 3D printing food. The third asked them to report any direct experience with 3D food and come up with potential applications for the technology. Of the 30 participants in the study, 12 had eaten 3D printed food before. The researchers found that prior familiarity with 3D printed food resulted in more positive scores on the first questionnaire. Participants were able to come up with a wide range of creative ways to apply 3D food printing [7]. The finding that understanding 3D food printing leads to better responses led us to include a short informational paragraph about how it works prior to the taste-test in our study—the Food Neophobia Scale in the follow-up questionnaire to measure attitudes towards 3D food.

Further research on neophobia towards novel foods showed the importance of understanding 3D food printing on decreasing neophobia. In another survey-based study by Brunner et al. [6], researchers wanted to know if teaching participants about 3D food printing would allow them to overcome their food neophobia. Two questionnaires and an informational packet were mailed out to Swiss citizens. The first questionnaire assessed their overall knowledge and perception of 3D food printing. The majority of the participants had very low initial knowledge. After completing the initial assessment, participants read some information about how 3D food printing works and four different ways it can be applied. Finally, they answered the second questionnaire that assessed how and if their attitudes changed. The researchers were somewhat successful; they overcame 3D food neophobia, but not 3D food printing technology neophobia. Explaining to participants that the printing process does not change food composition allowed them to move past their aversion to the potential of eating 3D food. However, participants were still unable to view a 3D food printer as kitchen equipment; it was still a strange technology that did not have a connection to food [6]. The success in overcoming food neophobia after the reading reiterates that it is vital to inform participants about 3D food printing in order to increase their willingness to eat 3D food.

Though useful, these findings about overcoming food neophobia come from surveys without a taste-test component. A study conducted by Mantihal at al. [9] was able to use real 3D printed food for participants to taste-test. Thirty panelists semi-trained in food tasting completed two taste-tests. The first used 3D printed chocolate samples printed in honeycomb patterns with 25%, 50%, and 100% infill percentages. The panelists had to rank the three samples in order of preference based on appearance and hardness. In the second taste-test, the panelists were given a 3D printed chocolate bar and a traditionally produced chocolate bar and were asked to choose their favorite between the two. The only significant difference found was a preference for the appearance of the 25% and 50% infill patterns. The researchers also had a survey component, where they surveyed participants on the design of the samples and novel technology in general. Survey participants did not taste the samples, and were only shown pictures. The majority had heard of 3D food printing before, but had never seen it applied in real life and were impressed by the outcome. 3D food was positively perceived, despite the lack of knowledge about the process [9].

To summarize the findings in these studies, people have a great deal of interest in 3D food and its possibilities and generally have positive attitudes towards it. However, the lack of knowledge about 3D food printing contributes to 3D food neophobia. Rather than seeing 3D food printing as a potential source of sustenance for mankind, people tend to view it as a cool novelty. 3D food is viewed positively but not necessarily as food, people are especially impressed when they enjoy the taste. Providing more information about the technology will be beneficial to improving its perception as well.

Satiety

An important part of the project goal is to ensure that the 3D printed bar would be satiable as well as tasty and nutritious. Previous studies have shown that people do not feel full after eating something if they do not initially perceive it as something that will make them feel full. Rolls et al. [10] examined this more closely by focusing on how the volume of food served affects satiety. Twenty men were recruited to come to the lab for four non-consecutive days to eat three meals. A milk preload was served to the participants on three of the four days. The three milk preloads served were identical in energy content, but varied in volume (300 mL, 450 mL, & 600 mL). For the rest of the day, the participants were given a wide variety of meals to choose from and the amount they consumed at each meal was measured. Participants also had to report how full they felt throughout the day. Results showed that the largest volume preload (600 mL) made participants feel the most full, despite all the preloads having the same amount of energy [10]. It is expected that people would feel more full after seemingly consuming more. The implication of these findings for the study led us to consider the volume of the 3D printed bar.

How 3D Printing Affects the Military

How the U.S Military Uses 3D Printers

Currently, the United States Military uses 3D printers in their everyday lives. 3D printing makes daily tasks easier while deployed by reducing costs, keeping equipment up and running, and keeping troops safe. There are numerous branches within the U.S Armed Forces that are using 3D printers, such as the Air Force, the Marines, the Navy, and the Army.

In the Air Force, the F-22 Stealth Fighter was one of the first to receive a 3D printed part. The piece printed is a small part that goes in the cockpit. It is typically manufactured using aluminum, but it was 3D-printed using titanium. This was advantageous because titanium does not corrode as fast as aluminum. This allows the piece to last the rest of the aircraft's life span without having to be replaced. 3D printing also allows for aging pieces to be replaced faster, without having to wait for shipping of materials. There will be little to no downtime when aircrafts have to be out of service. Along with not having to pay for shipping of parts, it is cheaper to have the raw materials ready and manufacture the piece on your own to avoid labor cost. Finally, the United States Air Force will monitor the piece to see how it holds up, as well as installing similar parts in all F-22s from now on. The Pentagon hopes 3D printing will play a vital role in the future of the military's daily functions [11].

Also, within the United States Air Force, members of the Oklahoma City Air Logistics Complex team were able to successfully 3D-print and test an engine component in early June of 2020. The 3D-printed piece was an anti-ice gasket; the gasket is an essential piece of the safe operation of the TF33 engine. The TF33 engine powers essential equipment like the E-3, the B-52, and the E-8 Joint Surveillance Target Attack Radar System. Richard Banks, 76th PMXG delegated engineering authority engineer said, "One of the things we found in this collaboration is that we could potentially solve the supply shortage by reengineering and printing something and prove it was safe to fly. This type of engineering makes it easier to source materials, greatly reduces lead time and ultimately helps to reduce logistical and supply issues" [12]. Addressing the issue of supply chains is very important, especially during the COVID-19 pandemic, where many companies had to shut down production. Even as companies tried to recover from the pandemic, many continued to face issues with high demand. Still, they lacked the necessary means to fulfill the market demand due to a shortage of workers and raw materials. Many companies were shut down, but the military had to continue working through the pandemic. They still needed supplies to replace broken parts of their equipment. As of August 2020, the REACT lab has been able to print 30 anti-ice gaskets. They were able to reduce the amount of time between an initial contract and actual component manufacture from 120-136 days to 14-21 days. Even though the anti-ice gasket is a fairly simple component, the Air Force is hopeful that 3D printing will allow for more complex and critical components to be implemented in the future [12].

Another branch of the military that is implementing 3D printing is the Marines. They were able to print a rocket launcher shelter in 36 hours. The entire structure was made entirely of quick drying concrete. The ICON's Vulcan 3D printer made a structure that can hold a HIMARS truck-mounted multiple rocket launcher system. The HIMARS measures 10 feet 6 inches tall, 23 feet long, and 7 feet 10.5 inches wide. The implications of a 3D-printed durable structure is that it can virtually be printed anywhere Marines are deployed. It can be used for shelter to protect supplies, vehicles, and personnel from extreme weather conditions. Another aspect in which the Marines are using 3D printing is in printing smaller parts of various equipment like buckles and pieces of equipment for drones to make them more customizable and tailored to their needs. They even have a system to set up to share ideas and receive feedback to make adjustments to them and push out the new adjustments to the rest of the corps [13].

Lastly, the Army uses 3D printers to reproduce pieces of equipment that are no longer in production. The Black Hawk has been used in the military for over 41 years and has been very valuable to operations within the Army. However, production of Black Hawks has stopped over 15 years ago, meaning that replacement parts are very difficult to find. Even though the Black Hawks are no longer being produced, the Army and Military still have plans to continue to use the Black Hawks for at least another 10 years. 3D printing has allowed the Army to replicate and print broken parts without having to wait years to find and buy parts. It can be especially difficult to find vendors with parts that are not used often or low volume parts within a reasonable time frame. Although 3D printing is incredibly useful for printing equipment parts, it is now being applied to other vital parts of the military: feeding the warfighters in it [13].

History of Meals Ready to Eat (MREs)

The United States Army currently depends on Meals-Ready-to-Eat (MREs) as one source of food for its warfighters. MREs are field rations that were originally created to provide nutritious meals. MREs use a water-activated exothermic reaction to heat up the food. They became standard issues in 1986, but the idea of food rations can be seen as far back as the Revolutionary War. At this time, rations were beef, peas, or rice. During the Civil War, the U.S Army gave out canned food that was less perishable. By World War I, they realized that canned food was very heavy and transitioned to salted or dried foods. By the second World War, the Army learned that providing basic nutrition was not enough for those on the field. They gave a variety of options tailored to warfighters in different environments. By the time the official MREs were being regularly produced, there were already 12 different meals on the menu. In 2021, there were 24 options with a vegetarian option as well [14].

MREs Perception & Effects of Long-Term Consumption

Since MREs were first developed, the meal options have expanded [1]. However, MREs have not been fully accepted by warfighters. The Brazilian Army also uses MREs to feed their warfighters and funded a study that compared the taste and nutrition of MREs to freshly prepared meals (FPMs). The main benefit of using MREs is the lack of a need for temperature control; they do not require refrigeration for storage or heating for consumption. However, no matter how much meal options expand, it is not possible to make any FPM into an MRE. The heavy processing to make the MRE also removes nutritional and rheological properties from the food. This leads to a monotonous diet that warfighters quickly grow tired of. This effect was seen in a study by Carvalho et al. [1] comparing FPM to MREs. Ninety-two male Brazilian warfighters were recruited to participate. The study went on for 21 days to test the acceptability of MREs over a longer period, along with the sensory analysis. Researchers developed seven meals in both a MRE and FPM version. The meals were selected from the weekly menu at the base based on which ones warfighters preferred most prior to the study. The chemical composition of all the meals was analyzed to determine the nutritional breakdown and moisture content in the food. Meals were served to the warfighters in the usual dining hall at lunch and dinner. The warfighters used a 9-point hedonic scale to evaluate each meal. Their plates were weighed before and after eating to measure the volume they consumed. The acceptance and sensory analyses from the first MRE day and the twenty-first MRE day were analyzed and compared. Results from the chemical composition analysis showed that the MRE meals were higher in sodium and fat and had excess liquid ingredients. They did not have the same nutritional benefit as the FPMs. On the acceptance measure, MRE were equally or more accepted than FPMs. However, there was a steady decline in acceptance over the 21-day period. They found that 39.9% of the MRE meals were being discarded [1] this type of food waste is something the military hopes to prevent with 3D food printing technology.

In 1995, another study was conducted to see the effect on the body and popularity of eating MREs over a long period of time. The results of two extended studies [15] provided definition of the underconsumption problem of MREs over time and potential insight into its solution. The first group tested was in 1985, with U.S Army troops during a 34-day field training exercise at the Pohakuloa Training Area on the island of Hawaii. In 1993, the study continued where the Massachusetts Institute of Technology (MIT) paid student volunteers who were fed MREs as their only source of food over a 44-day period. The students were fed their meals in a small dining room. They were provided with hot and cold water to prepare their MREs, as well as a microwave oven. Both groups were fed the identical MRE rations. Data was collected on the energy intake and body weight change over the duration of MREs consumption. The following data was collected and can be seen in **Table 1** [16].

Table 1. *Effects of long-term feeding of MRE IV on paid volunteers and U.S. Army field troops*

	Duration of Feeding (d)	Energy Intake (kcal)	Body Weight Change (lbs)
Field*	34	2,189	-10.4
Laboratory†	44	3,149	-1.5

* Field study used U.S. Army troops from Pohakuloa Training Area, Hawaii. SOURCE: Adapted from Hirsch et al. (1985).

† Laboratory study used paid student volunteers from Massachusetts Institute of Technology, Cambridge, Massachusetts. SOURCE: Adapted from Hirsch and Kramer (1993).

In **Table 1,** it can be seen that the students in the lab's energy intake was greater than those in the field by around 1000 kcal. The warfighters in the field also lost an average of 10.4 pounds, versus the students in the lab that only lost around 1.5 pounds. The warfighters lost on average seven times more weight than those students in the laboratory. A 9-point hedonic scale was used for participants to rate the MRE. The students in the lab rated the MRE an average of 6.05, while the warfighters found the MRE more acceptable with an average hedonic rating of 7. The study was repeated in 1986 with newer versions of the MREs with larger portions and slight changes to the menu. One was an improved MRE, and the other two were versions of the rations from the original. Overall, there was less noticeable weight loss for the troop groups that were studied over 11 days. The troops rated the food on a hedonic scale again, but this time they rated the different food categories for the different MREs [16]. The acceptance ratings of the three versions of MREs can be seen in **Table 2**.

Table 2. *Acceptance rating of the three versions of MREs by food class*

Food Class	Acceptance Rating Improved MRE	MRE VII	MRE IV
Entree	7.6*	6.8†	5.7‡
Starch	7.4*	7.0†	6.0‡
Spread	7.7*	7.4*†	6.6‡
Fruit	8.3*	7.5†	6.9‡
Dessert	7.4*	7.4*†	6.5‡
Fruit beverage	8.3*	8.2*	—
Other beverage	8.2*	7.5†	7.6†‡
Candy	8.6*	7.8†	6.8‡

NOTE: Means that do not share a common superscript are significantly different at $P < 0.05$. Group comparisons are based on Student-Newman-Keuls post-hoc tests following a one-way analysis of variance where the overall F indicated significant overall group differences. — = The MRE IV as tested did not include a fruit beverage. SOURCE: Adapted from Popper et al. (1987).

Overall, the improved MRE received the highest scores compared to the MRE Version Four and Version Seven. Version Four was the MRE tested in the first study, which received the lowest scores overall. Even with the improvements made to the MREs, much work has to be done in order to ensure that warfighters are getting the necessary calorie intake and nutrition from meals.

3D Food Printing in the Army

The United States Army Natick Soldier Research, Development, and Engineering Center (NSRDEC) is working with 3D printed food as the future of MREs. Their goal is to have customizable meals for individual warfighters to increase calorie intake and reduce waste. In the future, the Army hopes to combine wearable technology and 3D food printers to track physiology so warfighters can then print MREs customized to their nutritional needs. This new technology is projected to be ready as early as 2025. For example, if one warfighter needs more Vitamin C, the 3D food printer would print a food product with the correct amount of Vitamin C according to their wearable technology. If a warfighter needs to be up for many consecutive hours, their meal could include some extra caffeine or nutrients that help fight fatigue. Although 3D food printing technology can provide many options in the future, it is still fairly new and years away from being implemented in the Army due to the limits on printable food textures and ingredients. Mary Sceerra, a food technologist from NSRDEC, talked about the feasibility of implementing 3D printing to produce MREs. According to Sceerra, “it could reduce costs because it could eventually be used to print food on demand. For example, you would like a sandwich, whereas I would like ravioli. You would print what you want and eliminate wasted food" [17]. Lauren Oleksyk, another food technologist with NSRDEC, said "the technology could be applied to the battlefield for meals on demand, or for food manufacturing, where food could be 3-D printed and perhaps processed further to become shelf stable. Then, these foods could be included in rations" [17]. The research center in Natick is optimistic about the future of 3D food printing MREs.

Problem Statement

The goal of this work was ultimately to develop a calorie-dense, nutritious bar with equivalent (or better) hedonic properties as standard products. The bar was also intended to be satiable enough to keep warfighters full for long periods. Unlike traditionally sourced and produced food, 3DFP moves customization further up the supply chain to the point of consumption. The US Army Combat Capabilities Development Command Soldier Center (CCDC SC) has expressed interest in taking advantage of 3DFP customizing abilities for its troops to reduce waste, increase calorie intake, and improve nutritional value. Printing parameters, such as infill density and infill patterns, were important to explore as well, as they provide information on the mechanical strength of the bar. The end goal was to avoid warfighters' body weight loss while increasing calorie consumption. Testing different printing parameters allowed correlations to be made to mechanical strength and consumer perception. In the second part of this study, a consumer rating study was conducted in the lab with human subjects to assess the bars' psychosocial properties, including participants' satiety, hedonic ratings, and perception of the bar as food. How much participants consumed was recorded, as increasing calorie consumption is a chief goal of the CCDC SC. The data from this taste test was analyzed to feedback into the first phase and support the iterative improvement of the bar. When producing the bar, the printing parameters and qualities of printable material were measured and determined. These qualities were identified through physical tests such as three-point bend tests and compression tests. Understanding these parameters lead to more efficiency in the 3D food printing process and can be used in future research.

Methodology

The goal of this project was to design a three-layer 3D printed nutritional bar, explore and determine optimal printing parameters, investigate texture variation, and conduct consumer rating tests on participants. The U.S. Army Combat Capabilities Development Command (CCDC) Soldier Center (SC) is interested in exploring food additive manufacturing (also known as 3D printing) to provide personalized nutrition for warfighters in real-time. Along with personalized nutrition, exploring structural and visual elements like wall thickness, infill density, infill pattern, color, volume, and more is important to the CCDC SC. For the purpose of this study, only a few parameters were studied. These parameters can influence individual consumption behavior, which can be instrumental in the future of MRE consumption. In order to achieve this goal, five main objectives were identified:

1. To design an energy-dense bar formulation with optimal nutrition intake and satiety.
2. To identify optimal printing parameters for three discrete layers.
3. To investigate texture modifications on the bar's mechanical strength by manipulating different post-processing conditions.
4. To investigate texture modifications on the bar's mechanical strength by manipulating different printing parameters, in particular:
    i) Infill density
    ii) Infill shape
5. To investigate and analyze consumer rating/perception of 3D printed bar

In completion of this Major Qualifying Project (MQP), two 3D printers were used, Natural Machines Foodini ("Foodini") and the Hyrel MK1-250 polymer printer ("Hyrel"). The Foodini was used at the start of the project for preliminary formulations; research then shifted to the Hyrel because of its advanced capabilities. The Foodini is comparable to a household appliance or one that might be used at a restaurant. The interface is necessarily user-friendly. The Hyrel is a designated polymer printer capable of printing food feedstock with the ability to manipulate printing parameters like traditional printers. The Foodini was used for objective one and part of objective two, and then the Hyrel was used for the remaining objectives. Each 3D printer had its unique features that changed the way the project was approached.

Objective 1: To design an energy-dense bar formulation with optimal nutrient intake and satiety

The first objective was to design an energy-dense bar with optimal nutrition intake and satiety. The CCDC SC mentor tasked the team with creating a three-layer nutrition bar, with the specification that the first layer included oats and nuts. The research team was tasked with determining all the other design features. Research was done to find formulations with complementary flavors to design a three-layer bar with CCDC SC's specifications in mind. Initial formulations were found in the Foodini technical literature; other formulations were found on various nutritional platforms to have diversity in ingredients and techniques before deciding on a final formulation. Before going directly to 3D printing, the different formulations were tested in a kitchen to see if any formulations were not suited for printing.

Once the formulation that best fit the criteria was chosen, adjustments were made to ensure all the ingredients were shelf-stable. Exchanging ingredients for shelf-stable alternatives was important because in the military, MREs are kept for three years. With the CCDC SC's future goal of integrating 3D food printers in the field, the ingredients need to have the ability to be kept for long periods of time in varying climates before they are printed. The printed items do not necessarily need to be shelf-stable because they are meant to be eaten in real-time, but the ingredients used to make these items need to be. Along the way, adjustments were made to the formulation to enhance taste and increase printing performance.

Layer One

The first layer of the bar was primarily composed of oats and nuts, specifically almonds. From the first formulation to the final formulation, many changes were made. The first decision was a formulation that had to be post-processed. In the context of this project, post-processing is defined as the additional step of baking the material after printing. The post-processing decision was determined because the post-processed formulation allowed for more manipulation of texture. This layer was post-processed by placing it in a toaster oven at a specified temperature and time deemed optimal by the iterative testing performed in Objective 3. A combination of changing ingredients, preparation methods, and printing parameters had to be changed to achieve optimal taste and printability.

An example of this was replacing ground chocolate chips with cocoa powder to prevent clogging in the 1.5 mm (diameter) nozzle. Unfortunately, the addition of the cocoa powder overpowered the taste of all the other ingredients, so the chocolate chips were reintroduced. Next, the printing method was adjusted to avoid clogging. Before printing, the capsule was heated using the Foodini's built-in heating setting to melt the small chocolate pieces within the first layer formulation. The changes made from the first formulation to the final were the replacements of butter to coconut oil and crushed almonds to almond flour. These changes were made to improve the printability, taste, and to increase the ingredient's shelf stability. A full list of ingredients for this layer can be found in **Table 3** below. Images and nutrition facts of each ingredient can be found in **Appendix A.**

Table 3. *Ingredient list for layer 1*

Component	Amount(g)	Brand
Whole Grain Oats	2.53	Quaker Oats
Blanched Almond Flour	2.81	Good & Gather
Ground Cinnamon	0.13	Whole Foods
Freeze-Dried Apple	3.22	ONETANG
Organic Coconut Oil	1.09	Carrington Farms
Honey	3.88	Good & Gather
Water	7.66	Polar Spring
Vanilla Extract	0.61	Pics
Sunflower Butter	1.17	SunButter Natural

Layer Two

The second layer was a fruit layer designed to complement the oats and nuts layer. A common ingredient between the two layers consists of freeze-dried apples and cinnamon. Unlike the first layer, the second layer was not post-processed to provide a different texture. The texture of the first layer was crunchy, while the second layer resembled a thicker, higher viscosity jam. First, a fruit leather was attempted but was quickly ruled out due to the extensive time requirement. A simple jam was also attempted by reducing frozen fruits in lemon and water, but the process length was also deemed too long. The jam also was problematic when the smaller nozzle sizes were used, as the strawberry seeds' size was too big to go through the nozzle, making it hard to print. The strawberry jam flavor did not complement the flavor of the first layer either, so the ingredients had to be reformulated. Since the first layer had apples, it was decided to keep the theme of apples consistent and use applesauce and apple cinnamon rice cakes in the second layer. These alterations allowed us to keep an apple flavor throughout the bar while not introducing long processing times or large particles that could clog the extruder. Applesauce can pass through the 1.5mm nozzle with no clogging issues. The viscosity of applesauce is relatively low, so it can be paired with other ingredients like honey to increase the viscosity for optimal printing. A full list of ingredients can be seen in **Table 4** below.

Table 4. *Ingredient list for layer 2*

Component	Amount(g)	Brand
Cinnamon Applesauce	1.98	Motts
Blanched Almond Flour	1.21	Good & Gather
Apple Cinnamon Rice Cakes	0.414	Quaker Oats
Freeze-Dried Apple	0.307	ONETANG
Almond Butter	2.22	Good & Gather
Honey	2.26	Good & Gather

Layer Three

The third layer, a dark chocolate cubic design, was added to make the bar more visually appealing and counteract the sweetness of the first two layers. Dark chocolate chips were finely chopped using a food processor and then heated to the temperature of tempered (120-130°F) chocolate so that the chocolate could resolidify. Resolidifying the chocolate resulted in more texture in the bar. In the Foodini, the chocolate was melted inside the capsule with the heating setting before being printed. When the full bar formulation was switched to the Hyrel, the chocolate had to be heated using a double boiler system. This process required the chocolate at an ideal temperature where it was not fully melted but rather a smooth, pliable consistency. This layer is also not post-processed. A full list of ingredients for this layer can be found in **Table 5** below.

Table 5. *Ingredient list for layer 3*

Component	Amount(g)	Brand
Dark Chocolate	1.10	Nestle Toll

Objective 2: To identify optimal printing parameters for three discrete layers

Once we had finalized the formulation of the bar, the research team then had to determine the optimal printing parameters for both the Foodini and Hyrel machines, respectively.

Foodini

The Foodini is a device that connects via the internet with a built-in touch screen for operating the machine. Once the user chooses the recipe they want to print, the Foodini will instruct the user on what ingredients and or foods to put in each capsule. The user also has the option to create their own ingredients that the Foodini does not have pre-set. The capsules are made out of stainless steel, and the bottoms can be removed to change the nozzle size. The nozzles sizes that were used in this study were the 1.5 and 4.0 mm nozzles. The Foodini capsules had the ability to be heated through a heating temperature setting, before or during printing. Capsules were loaded, then a shape was chosen or created to be printed. Ingredients new to the Foodini had to be calibrated to determine optimal printing parameters for that specific material.

Nozzle size (diameter) is an important parameter to consider. The bar formulation is directly affected by the nozzle size; smaller nozzle diameters require smaller particle sizes in the bar ingredients. The different nozzle sizes available for the Foodini were 1.5 mm and 4.0 mm. In the early stages of the project, a 4.0 mm nozzle was used to allow for more diverse particle sizes to be used. As the project progressed, the formulation had to be altered to allow the material to flow through the 1.5 mm nozzle. Due to the nature of the experiments with different infill densities and patterns, having a smaller nozzle size also allows for better control when printing intricate patterns and a better resolution overall.

When printing a new ingredient in the Foodini, the ingredient required calibration using a standard in the form of printed lines. The Foodini prints calibration lines so that the user can determine the optimal printer parameters, which can lead to user error. The formulations differ for each layer. Therefore, for each layer, a new ingredient had to be created in the Foodini due to that material's physical properties, which required unique printing parameters. The Foodini calibration tests for the four most common advanced settings within its program, which include ingredient flow speed, print speed, the distance between layers, and fill factor. In order to calibrate each material, seven calibration lines were printed representing different printing conditions within those four categories. The lines that looked the cleanest, smoothest, and most consistent were considered the optimal printing parameters. In **Figure 2**, the calibration lines can be seen. The advanced printing parameters for the Foodini can be found in **Appendix B**.

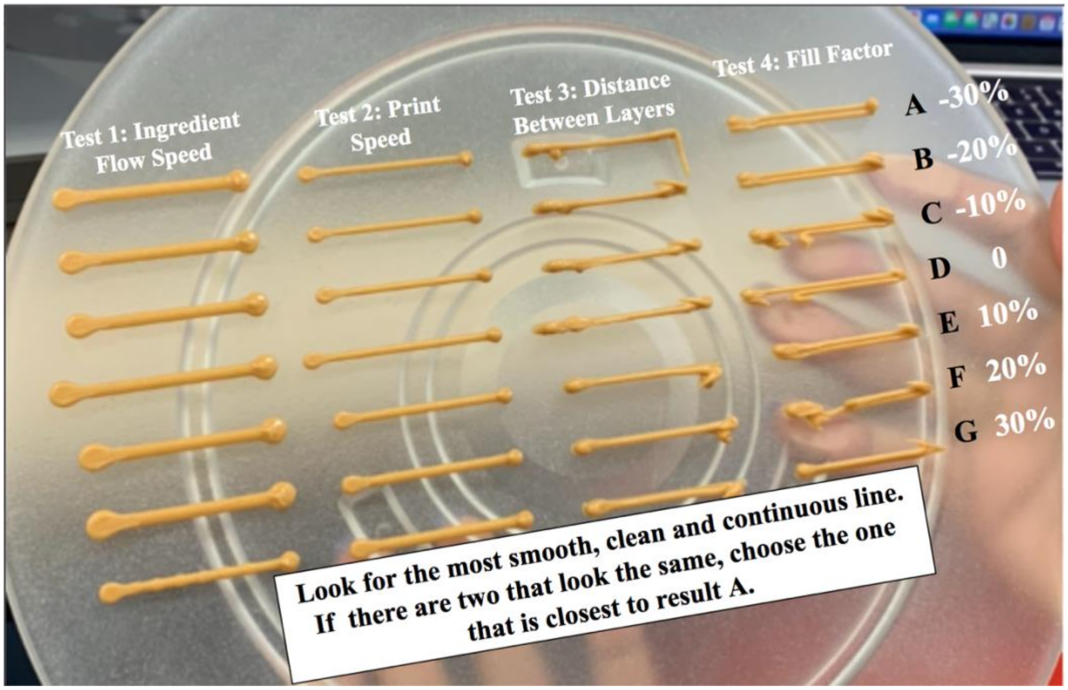


Figure 2. *Foodini's seven calibration lines for four different categories for optimal printing parameters adapted from [18]*

Hyrel Engine Standard Resolution (SR)

The Hyrel printer uses plastic syringes with varying nozzle sizes. Unlike the Foodini, the Hyrel is a steep learning curve for individuals who did not have previous knowledge of 3D printers. To use the Hyrel, a computer-aided design (CAD) was created and saved as an .STL file (the triangulation of a geometric file generated in a CAD program). Ultimaker Cura is a slicing software used to convert digital computer models to a model 3D printers can understand. The user can apply more general print settings like flow speed, infill density, infill pattern, etc., which will be explained further in Objective 2. The slicer program then applies the user-determined setting and divides the 3D shape into layers accordingly. These layers are then converted into a .GCODE file, which is a language that the printer can understand. The .GCODE tells the machine what coordinates to go and the action to execute at the coordinates, also known as "tool paths." There were many Ultimaker Cura and printer settings that could have been manipulated. For the scope of this project, only a few were chosen to vary because they directly impacted texture, and that was one the CCDC mentor's recommendations to focus on. It should be noted that Ultimaker Cura was only used for the Hyrel printer as the Foodini, unlike common 3D printers, did not require designs to be sliced. In this section, the printer and Ultimaker Cura settings changed in this experiment and a description of their functions are highlighted. Printer settings are defined as the settings in the program Repetrel, the Hyrel printer software where all the controls to print are.

The Ultimaker Cura settings changed to find optimal printing parameters were print speed, layer height, infill density, and infill pattern. Print speed is the speed at which the print is printed in units of millimeters per second (mm/s). This was an important variable since having a low print speed will lead to a higher resolution. However, because the print speed is lower, it increases the bar's print time. The inverse of this situation is having a higher print speed but lower resolution.

Print speed is even more critical when printing with plastic filaments in traditional 3D printers, because the nozzle sizes are very small and require a heating element as well. The standard nozzle diameter for most 3D printers (printing plastic filament) is 0.4mm. The Hyrel uses a nozzle diameter of 1.5mm because it is printing food, allowing prints to be much faster. Layer height is important because it determines how many layers there are and how thick they are if the dimensions are consistent. Infill density and infill pattern are covered more in depth in Objective 4.

A few printer settings in the Hyrel's printing software, Repretel, were manipulated to identify optimal parameters. The Repretel printer settings manipulated were the pulses per microliter and the flow multiplier. Pulses per microliter are a certain number of pulses on the motor that generate a certain volume displacement. Other factors play a role in the pulses per microliter. The time of displacement and the actual extrusion time might be delayed due to various factors like viscosity, compressibility, and nozzle characteristics. The flow multiplier allows for live percentage-based flow calculations. For example, a material flow rate multiplier of 1 would be there's no modification, but 0.90 would mean 10% less flow. On the other end of the spectrum, if the flow multiplier was 2 it would be 200% more flow. These two settings were the most important because they had the biggest impacts on print quality and time when adjusted. Printer settings can be changed in real-time, so the pulses per microliter and flow multiplier were adjusted in real-time to find the best values for the best print. In **Appendix C**, a full list of Ultimaker Cura settings, and in **Appendix D**, Repetrel settings can be seen.

Objective 3: To investigate texture modifications on the bar's mechanical strength by manipulating different post processing conditions.

For this objective, a feasibility study was performed. The goal was to determine a range of viable post-processing times and temperatures. A matrix of times and temperatures was created for post-processing conditions, as shown in **Table 6**. A wide range of temperatures and times were chosen to produce various textures, one extreme being raw and the other burnt. It should be noted that this experiment was executed solely on the first layer as this was the only layer that required post-processing.

Table 6. *Temperature and time matrix, temperatures ranging 275 ℉ to 350℉ and times ranging from 10 to 25 minutes.*

Temperatures Times	275 °F	300 °F	325 °F	350 °F
10 min	x	x	x	x
12 min	x	x	x	x
15 min	x	x	x	x
18 min	x	x	x	x
23 min	x	x	x	x
25 min	**x**	x	x	x

The goal was also to discover the relationship between the texture/post-processing conditions and the mechanical strength of a bar. As mentioned earlier, what differentiates 3D food printing from other methods in the food industry is its ability to be customizable. The data collected from this experiment was used to determine the post-processing time and temperature combination for the taste test bars in the consumer rating pilot study described in Objective 5. The MultiTest 2.5-dV(u) machine was used to conduct mechanical strength tests on the different variations of the first layer. A three-point bend test was performed to find Young's modulus and maximum load. The three-point bend test produced raw data as well as some calculated values. The raw data that it outputs are load (N), time (s), displacement (mm), stress (Pa), and strain (%). The values calculated by the software were: max load (N), Young's modulus (Pa), offset yield (Pa), and ISO 6892 break (%). The Young's modulus and maximum load were of great interest. Young's modulus measures how stiff a material is and can be calculated by taking the slope of the elastic region. The max load will tell us how much weight the bar can withstand before it cracks and loses its shape. Figure 3 displays a bar after the maximum force has been applied.

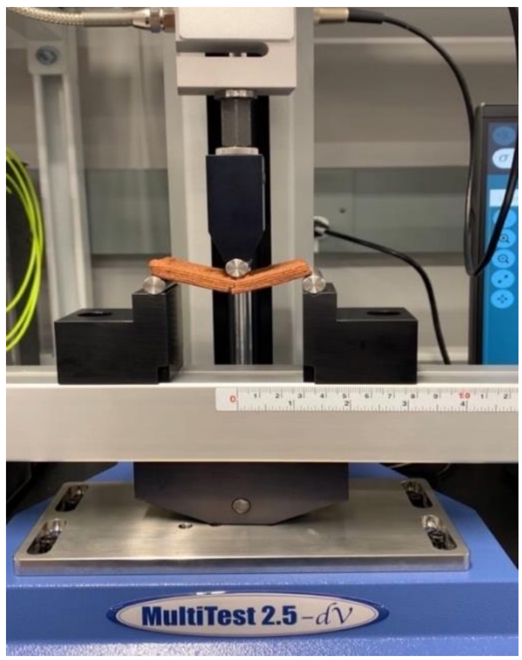


Figure 3*. Bend test sample with a force exceeding the maximum load.*

To find Young's modulus, the slope of the stress versus strain curve had to be determined. The equations the software used to solve flexural stress, flexural strain, and Young's modulus can be seen in **Equations 1-3 respectively**. Where l, b, and h stand for length, width, and height in centimeters, respectively. F represents the force, and D represents the maximum deflection of the center of the beam. The results of this experiment can be used to connect the texture and mechanical properties of these bars. An acceptable range of Young's modulus can be determined and related to the various post processing times and temperatures based on raw data, visual appearance, and taste.

$$\sigma_f = F \times \frac{3l}{2bh^2}, Pa \quad (1)$$

$$\epsilon_f = D \times \frac{600f}{l^2}, \% \tag{2}$$

$$\lambda = \frac{stress}{strain}, Pa \tag{3}$$

Using the same MultiTest 2.5-dV(u), compression tests were also run. The compression test was solely run on the six bars post-processed at 300 °F. It was determined that 300 °F was the optimal post-processing temperature because it allowed the bar to be post-processed evenly all the way through within a reasonable amount of time. A reasonable amount of time would be anything under 30 minutes to be efficient to be able to print and post-process bars back-to-back. Greater temperatures, while requiring less time in the toaster oven, did not bake the bar evenly. The edges would be charred when the center would be undercooked. Lower post-processing times took longer to bake both the exterior and interior of the bar. A 2.0 by 4.0 cm sample was needed for this experiment. The software was set to apply the necessary force to reach a compression displacement of 3.0 mm. The load required to achieve this displacement depended on the strength of the bar. A displacement of 3.0 mm was chosen because it was the highest displacement value available for the instrument. Similar to the three-point bend test, the maximum load was recorded. **Figure 4** shows a sample post-processed at 300°F for 18 minutes being compressed by the MultiTest 2.5-dV(u). The goal was to compare the maximum load to the human bite force (i.e., 285 N). For instance, a low load indicates a bar that is easy to bite. On the other hand, if the values of max load and human bite force were close to each other, this implied the bar was harder to bite.

Figure 4. *Compression test on a sample post processed at 300°F for 18 minutes.*

Procedure:

*The printing preparation protocol in **Appendix E** was followed to create the first layer to perform this study. The slicer printing parameters shown in **Appendix C** were set in Ultimaker Cura, a well-known slicer application for 3D printers, to generate the G-code. Another set of printing parameters is shown in **Appendix D** representing the Hyrel printing parameters that were used. 28 time and temperature combinations were chosen to conduct the bend test to determine viable conditions for layer one of the three layer bar. Six different post processing times at a* *temperature of 300℉ were compression tested to determine the easiness of a bite. An infill density of 100% and a zig-zag infill pattern was used for all the samples in this experiment. Two trials for each test were conducted to get more accurate data. A toaster oven was used to bake the samples at the predetermined conditions. Before the bend and compression test was performed, each sample was allowed to cool down for at least 2 hours. The tests were then performed in the MultiTest 2.5-dV(u) machine. Each bar's yield modulus and max load force were recorded and compared.*

Objective 4: To investigate texture modifications on the bar's mechanical strength by manipulating different printing parameters

The next objective was to investigate texture modifications on the bar's mechanical strength. The texture of 3D printed foods can be manipulated through the variation in interior structure (Mantihal, 2019). Knowing this, two printing parameters were varied to change the internal design of the bar. The two printing parameters varied for this experiment were the infill density and the infill pattern because they both impact the bar's texture and, therefore, the mechanical strength. It should be noted that this experiment was executed solely on the first layer as this was the only layer that was post-processed, allowing for manipulations to run strength tests.

Infill Density

The first parameter that varied the internal structure was infill densities. Infill density controls the fullness of the bar and how much material is needed. Similar to traditional 3D printed materials, the infill density significantly affects the mechanical strength, weight, and printing time of 3D printed food material. Higher infill densities require more material, while lower infill densities require less material. It was decided to keep the dimensions of the bars consistent since varying the infill density varied the mass of the bar. The dimensions of the bars were fixed at 5.29 x 5.29 x 0.75 cm. The infill pattern of zig zag was also consistent throughout this experiment. Since the mass of the bars varied, the post-processing conditions had to vary as well. The post-processing temperature was fixed at 300 F while the post-processing times were varied. It was assumed that the mass of the bar and the time needed to bake the bar all the way through were proportional. The infill density of 100% and mass of 26.5 grams was used as a base for the post-processing time and mass calculations. The 100% infill bar was post-processed for 20 minutes, so it was assumed it took about 0.75 minutes to bake 1 gram. This number was then multiplied by the mass of the bars with the different infill to determine the required post-processing times. **Table 7** displays the mass and post-processing conditions of each bar tested in this experiment.

Four different infill densities of the base layer (40%, 55%, 75%, and 100%) were tested to discover the relationship between infill density and mechanical strength. Similar to Objective 3, mechanical strength of the bar was measured by a three-point bend test. The young modulus and maximum load were calculated and recorded. This data could then be mapped back to consumer ratings allowing an ideal young modulus or max load range to be determined.

Table 7. *Infill density experiment specifications*

Infill Density	40%	55%	75%	100%
Mass (g)	14.27	16.94	20.98	25.29
Conditions (°F, min)	300, 11	300, 14	300, 18	300, 20
Print				

Procedure:

The printing preparation protocol in ***Appendix E*** *was followed to create the base layer to perform this study. The slicer printing parameters shown in* ***Appendix C*** *were set in Ultimaker Cura, a well-known slicer application for 3D printers, to generate a G-code that was uploaded to the printer. Another set of printing parameters is shown in* ***Appendix D*** *representing the Hyrel printing parameters that were used. Infill densities tested were 40%, 55%, 76% and 40%. Two trials were conducted for each infill density to get more accurate data. A toaster oven was used to bake the sample at the predetermined conditions. After the bars were post-processed and allowed to cool down for at least 2 hours, a bend test was performed in the MultiTest 2.5-dV(u) machine. Each bar's yield modulus and max load force were recorded and compared.*

Infill Pattern

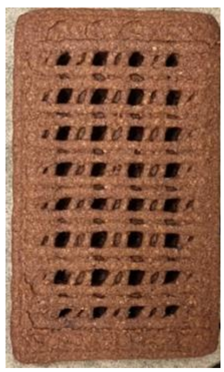
The second parameter that varied in this experiment was the infill shape. Infill pattern controls the interior shape and structure of a material. Infill pattern also affects the 3D printed material's mechanical strength. Unlike the infill density, different infill patterns theoretically required the same amount of material for a print with the same dimensions. All the bars in this experiment had dimensions of 4 x 7 x 0.75 cm. Therefore, the weight of the bars with varying infill patterns was consistent at around 26.5 g. The infill density was also kept the same at 80%. An infill density of 80% allows the infill pattern to be more visible. Due to the fact, the bars were approximately the same weight, the post-processing conditions were also kept the same at 300 °F for 20 minutes, allowing the infill pattern to be the only variable in this experiment. A summary of these specifications can be found below in **Table 8**.

Table 8. *Infill pattern experiment specifications*

Dimensions (l x w x h)cm	Mass (g)	Infill Density (%)	Conditions (°F, min)
4 x 7 x 0.75	*26.5*	*80*	*300, 20*

A three-point bend test was used to measure the mechanical strength of the bars with varying infill patterns. The young modulus and maximum load were calculated and recorded. Five infill patterns were tested and are shown in **Table 9**. The goal of this experiment was to discover the strongest infill pattern. This data could then be mapped back to consumer ratings allowing an ideal young modulus or max load range to be determined.

Table 9. *Ultimaker Cura infill patterns*

	Zig-zag	***Octet***	***Triangles***	***Concentric***	***Grid***
Infill Patterns					

Procedure:

The printing preparation protocol in ***Appendix E*** *was followed to create the base layer to perform this study. The slicer printing parameters shown in* ***Appendix C*** *were set in Ultimaker Cura, a well-known slicer application for 3D printers, to generate a G-code that was uploaded to the printer. Another set of printing parameters is shown in* ***Appendix D*** *representing the Hyrel printing parameters that were used. Infill patterns tested were zig zag, octet, triangles, concentric, and grid. Two trials were conducted for each infill pattern to get more accurate data. A toaster oven was used to bake the sample at the predetermined conditions. After the bars were post-processed and allowed to cool down for at least 2 hours, a bend test was performed in the MultiTest 2.5-dV(u) machine. Each bar's yield modulus and max load force were recorded and compared.*

Objective 5: To investigate and analyze customer rating/perception of 3D printed bar

Once a final prototype of the bar was completed, a pilot study was conducted to observe and collect data on consumer ratings to improve the bar. The data was collected in a series of steps. People with food allergies were not permitted to take part in the study. Participants were asked not to eat anything an hour prior to participating in the study to ensure they were not too full or hungry when eating the bar. The study took place in the Seed Lab, where they were read a series of instructions from a script to ensure that everyone was receiving the same information. The script can be found in **Appendix F.** The participants were placed in individual rooms to conduct the tests. Before starting the study, participants were asked to read a consent form to give consent to participate. The prototype bar was weighed in grams before and after being given to the participant to collect data on how much was consumed during the study. The participants were given a product rating form along with the bar prototype and asked to rank the bar in a number of categories and then overall. The categories and attributes the participants rated can be seen below in **Table 10**.

Table 10. *Product rating form categories/attributes that participants must rate during the first part of the pilot study.*

Categories/Attributes	Rating Scale	Key
Visual, Smell, Texture/Mouth-feel, Flavor, and Overall	1 to 6	1: extremely unappealing 6: extremely appealing
Saltiness, Sweetness, Bitterness, Sourness, Chewiness, Dryness, Crunchiness	-3 to 3	-3: Not (attribute) enough 3: Way too (attribute)

The attitudes were measured using the Cox and Evans's Food Technology Neophobia Scale [19]. These questions helped us gauge what to change for future iterations to improve the bar. Not only does it improve the taste of the bar but also links participants' responses to printing parameters, especially when it comes to texture. This made the participants' acceptability visible by ranking the chewiness, dryness or crunchiness of the bar. That way, changes could be made to printing parameters to improve the bar.

At the end of the product rating task, the participants were asked a series of yes or no questions: would the bar be satisfying as a snack? A meal? Would they purchase it if it were available in a store? These questions were asked to gauge if the bar was perceived as satiable, as well as if it is something participants enjoyed. The participants were also asked if they had ever tried 3D printed food. Past research has shown that people who have eaten 3D printed food before tended to enjoy 3D printed foods more [7]. An additional comments section was at the very end for participants to include any notes that they felt were not covered in the form. Having an additional comment section also allowed us to make changes to the form if there was a common theme within the responses. The product rating form was given on paper to guarantee that none of the computers would be damaged by food or water during the taste test.

The next step was taking the participants' weight and height. In food research it is common to take the weight and height to see if there is a link between eating behavior and body mass index (BMI). Reviewers of food studies also look for participants' BMI to be recorded so it is taken just in case for that very purpose. The last step was giving the participants a debriefing form where they could learn a little more about the study as well as the ingredients in the bar. It should be noted that the pilot study was conducted in conjunction with another MQP student Ellie Koptsev, who created the surveys, script, consent form, and debriefing form.

Results & Discussion

Post Processing Time & Temperature Matrix

Varying Time

The third objective was to investigate texture modifications on the bar's mechanical strength by varying the post-processing conditions. Multiple combinations of times (min) and temperatures (°F) were tested on the base layer (layer 1) created in Objective 1. A total of four temperatures and six times were evaluated. Young's modulus was used as the texture indicator, determining the stiffness of the bar. It was hypothesized that an increase in time would result in an increase in Young's modulus and maximum stress because the bar would have more time in the toaster oven to get crispier. The same was hypothesized for higher temperatures that the Young's modulus and max stress would increase with increasing temperature. Time and temperature had two different effects on the bars. It was hypothesized that time would have a greater Young's modulus than temperature because increasing the temperature does not necessarily indicate that external layers' texture resembled the interior layers. **Table 11 and Figure 5** display the raw data for 300 F at six time intervals ranging from 10-25 minutes.

Table 11. *Young's modulus and max stress for the post processing conditions at six time intervals ranging between 10-25 minutes at 300* °F.

Times (min) at 300 °F	Young's modulus (Pa)	Max Stress (Pa)
10	**Trial 1:** 2.56×10^6 **Trial 2:** 3.32×10^6	**Trial 1:** 17800 **Trial 2:** 19232
12	**Trial 1:** 3.82×10^6 **Trial 2:** 3.15×10^6	**Trial 1:** 21605 **Trial 2:** 11174
15	**Trial 1:** 3.15×10^6 **Trial 2:** 4.71×10^6	**Trial 1:** 36227 **Trial 2:** 36701
18	**Trial 1:** 1.01×10^6 **Trail 2:** 1.26×10^6	**Trial 1:** 14693 **Trail 2:** 20808
23	**Trial 1:** 9.17×10^6 **Trial 2:** 9.63×10^6	**Trial 1:** 93734 **Trial 2:** 105896
25	**Trial 1:** 13.25×10^6 **Trial 2:** 13.20×10^6	**Trial 1:** 179587 **Trial 2:** 115086

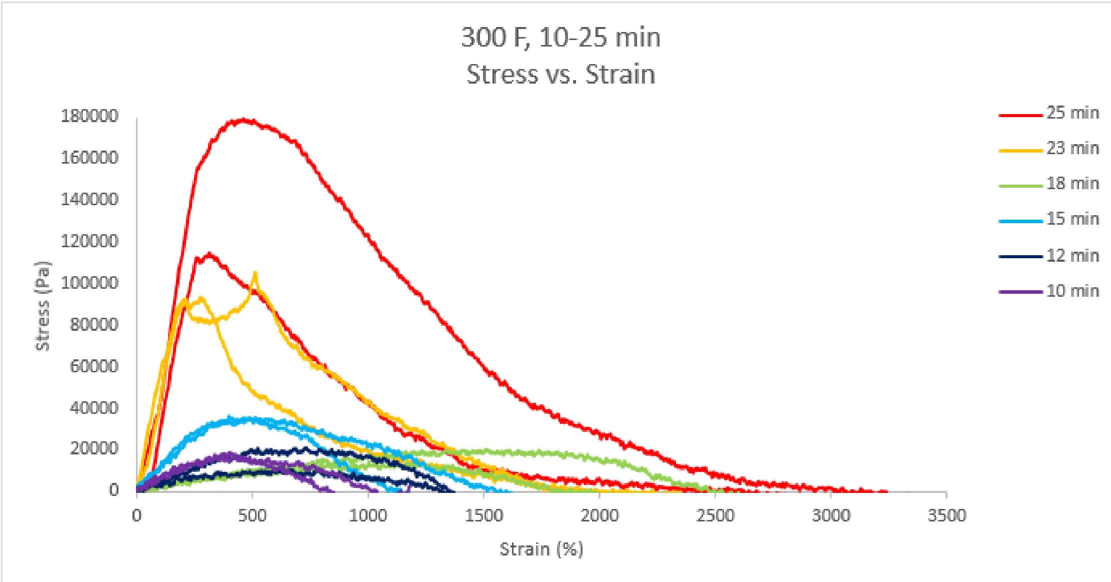


Figure 5. *Stress versus strain graph at 300°F for six time intervals, 25 min (red), 23 min (orange), 18 min (green), 15 min (blue), 12 min (indigo), 10 min (violet)*

The data supported the hypothesis that overall the Young's modulus increased with increasing time. There was one outlier, 18 minutes, that did not follow the trends as it was the lowest Young's modulus reported at 1.01 x 10^6 Pa. Analyzing the rest of the data, excluding the 18 minutes, the lowest Young's modulus was 10 minutes at 2.56 x 10^6 Pa, and the highest was at 25 minutes with a value of 13.25 x 10^6 Pa. This means the 25 minutes was the stiffest bar out of the five other time intervals. The most elastic bar was the bar at 10 minutes which was expected because it had the least amount of time to process and get stiff. The max stress data did not follow the trend as consistently because between trials, there was a lot of overlap between 10 and 12 minutes. The average max stress for 10 minutes (18516 Pa) was higher than 12 minutes (16390 Pa). There are two possible reasons why the 18 minutes data is so low. First, not all bars were baked on the same day, so the humidity in the room could have impacted the mechanical strength of the bar. The other possible reason for the bar being so elastic is that it sat out for longer than expected (around six hours) from when it was printed to when tested. If bars were left out for longer periods of time, they tended to lose their texture over time and become softer in texture. The rest of the stress versus strain graphs with varying time and constant temperatures can be seen in **Appendix G.**

Varying Temperature

It was hypothesized if the time was held constant and the temperature varied, the Young's modulus would increase, and the max stress would also increase. The reasoning behind the hypothesis is that increasing the temperature processes the bar at a faster rate for the same time. The data for a single time interval (25 minutes) held constant while the temperature was varied is displayed in **Table 12** **and** **Figure 6.**

Table 12. *Young's modulus and max stress for the post processing conditions at four different temperatures ranging between 275-350 °F at 25 minutes*

Temperature (F) at 25 min	Young's modulus (Pa)	Max Stress (Pa)
275	**Trial 1:** 6.02 x 10^6 **Trial 2:** 11.74 x 10^6	**Trial 1:** 87402 **Trial 2:** 134423
300	**Trial 1:** 14.19 x 10^6 **Trial 2:** 16.31 x 10^6	**Trial 1:** 115086 **Trial 2:** 179587
325	**Trial 1:** 10.13 x 10^6 **Trial 2:** 26.48 x 10^6	**Trial 1:** 291724 **Trial 2:** 397103
350	**Trial 1:** 18.62 x 10^6 **Trail 2:** 77.78 x 10^6	**Trial 1:** 316117 **Trail 2:** 583711

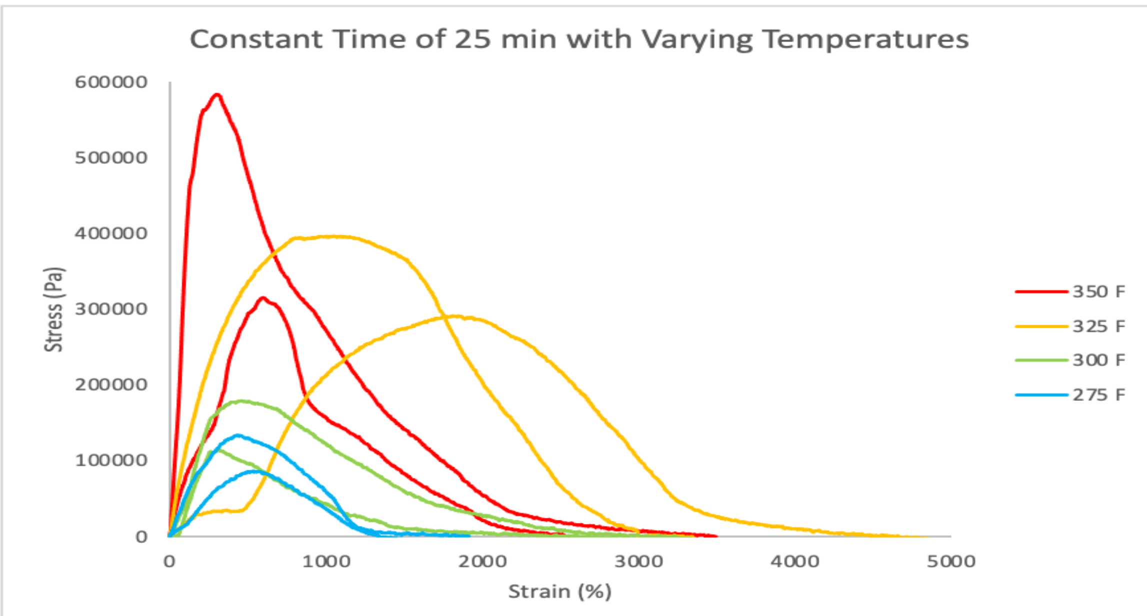


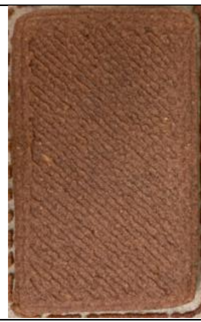
Figure 6. *Stress versus strain graph at 25 minutes for four different temperatures, 350 °F (red), 325 °F (orange), 300 °F (green), 275 °F (blue)*

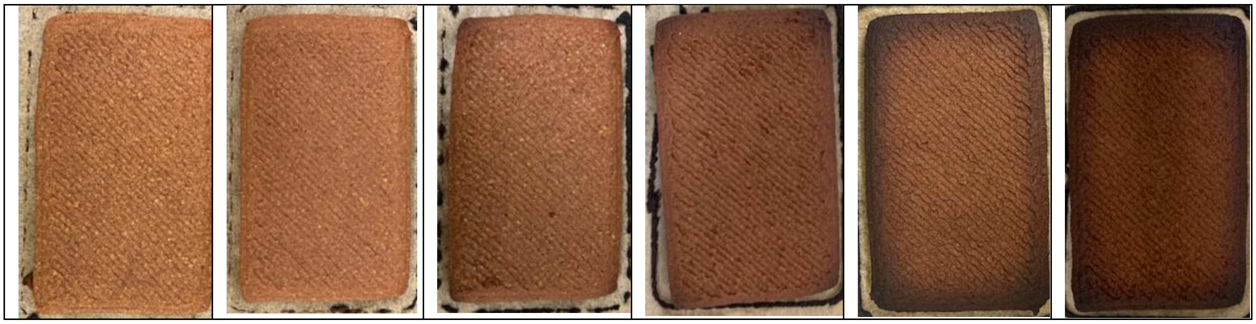
The data supports the hypothesis. **Table 12** shows the Young's modulus increases as the temperature increases. This means the bar is stiffer at higher temperatures and more elastic at lower temperatures. Young's modulus data ranges between 6.02 x10^6 to 77.78 x 10^6 Pa, with 275 F being the low end of the spectrum and 350 F being the high end. The max stress overall between trials increased as the temperature increased. Another trend that can be drawn is that the first trials had lower Young's modulus and lower max stress values compared to the first trial. A possible reason is the first trial was printed and processed first, so it had more time to sit than the second trial.

Viability Evaluation

Not only did varying post processing conditions change the texture (and therefore Young's modulus and max stress), but it also changed the appearance of the bar. **Table 13** displays images of each bar post processed at the specified post processing temperature and time combination. A clear gradient is shown both going across the time row and down the temperature column. As expected, the bars post-processed at higher temperatures and times had a darker color. Some of the bars were even burnt on the edges. The bars that had the best appearance and taste were post processed at 300°F which is why this temperature was used for the compression tests and the pilot study.

Table 13. *Post-processing temperature and time matrix photos*

Baking Temperature: 275F					
10min	12min	15min	18min	23min	25 min
					
Baking Temperature: 300F					
10min	12min	15min	18min	23min	25 min
					
Baking Temperature: 325F					
10min	12min	15min	18min	23min	25 min
					
Baking Temperature: 350F					
10min	12min	15min	18min	23min	25 min



Another goal of this experiment was to determine a range of viable post-processing conditions. To do this, the research team sampled each of the bars and recorded comments based on the bar's palate and appearance. These comments can be found in **Appendix H**. The research team then determined which bars were too raw or burnt and deemed unviable. Viable times were determined for each temperature. The viable post processing conditions were then related to the bar's mechanical property meaning the corresponding Young's modulus of the upper and lower ends of the viable range were identified, which can be seen in **Table 14**.

Table 14. *Viable Young's modulus range based on appearance and research team sampling*

Temperature (°F)	Viable Post-Processing Times (minutes)	Viable Young's modulus Range (Pa)
275	25	11.74 x 10^6
300	18, 23, 25	1.26 x 10^6 to 16.3 x 10^6
325	15, 18	2.77 x 10^6 to 12.5 x 10^6
350	15, 18	13.54 x 10^6 to 28.17 x 10^6

Compression Test

In addition to the bend tests and viability evaluations, the post processing condition experiment was conducted to compare the maximum load a bar post processed at 300°F, for six different time intervals, to the human bite force of 285 N. **Table 15** shows the table of the maximum load from the compression test of the six different bars. As shown, the maximum force needed to achieve a displacement of 3 mm for bars post processed for 10, 12, 15 minutes was much lower than that of a human bite force, implying that the effort needed to eat the bar is less. As the time increased, the force needed to compress the bar 3 mm increased as well. The bend test results confirmed that the stiffness of a bar increases as the post processing conditions increase. This explains why a greater load force is required to complete the desired displacement for greater post processing times because the bar has a larger Young's modulus.

Table 15. *Maximum loads required to achieve a displacement of 3 mm for bars post processed at 300℉*

Time Interval at 300 F	Maximum Load (N) Trial 1
10 Minutes	**Trial 1:**50.42 **Trial 2:** 42.10
12 Minutes	**Trial 1:** 88.86 **Trial 2**: 97.57
15 Minutes	**Trial 1:** 59.14 **Trial 2**: 71.162
18 Minutes	**Trial 1:** 66.33 **Trial 2**: 68.48
23 Minutes	**Trial 1:** 167.57 **Trial 2**: 152.95
25 Minutes	**Trial 1:** 148.73 **Trial 2**: 135.75

Infill Density

The second experiment conducted focused on manipulating the infill density, a printing parameter in the Ultimaker Cura settings. Ultimaker Cura is a slicer software it converts digital computer models to a code the 3D printer can read. As explained previously, infill density is the percentage of material present on the inside of the print. Four different infill densities were tested, 40%, 55%, 75%, and 100%. It was expected that the lower infill densities would have a higher Young's modulus because they were more brittle formless material and more space in between each "line." The higher density prints would have a lower Young's modulus because they were more filled in and thus be more elastic ("chewier"). It was expected that the higher infill densities would withstand a higher maximum load due to their internal structure. At least two trials were conducted for each infill density. The raw data can be seen in **Table 16**.

Table 16: *Corresponding Young's modulus and maximum load for each infill density tested for each trial.*

Infill Density (%)	**Young's modulus (Pa)**	**Max Stress (Pa)**
40%	**Trial 1:** 9.19 x 10^6 **Trial 2:** 2.51 x 10^6	**Trial 1:** 9917 **Trial 2:** 9862
55%	**Trial 1:** 5.04 x 10^6 **Trial 2:** 5.35 x 10^6	**Trial 1:** 9807 **Trial 2:** 9834
75%	**Trial 1:** 7.51 x 10^6 **Trial 2:** 5.24 x 10^6	**Trial 1:** 9928 **Trial 2:** 9963

100%	**Trial 1:** 2.11 x 10^6 **Trial 2:** 2.79 x 10^6	**Trial 1**: 9573 **Trial 2:** 9959

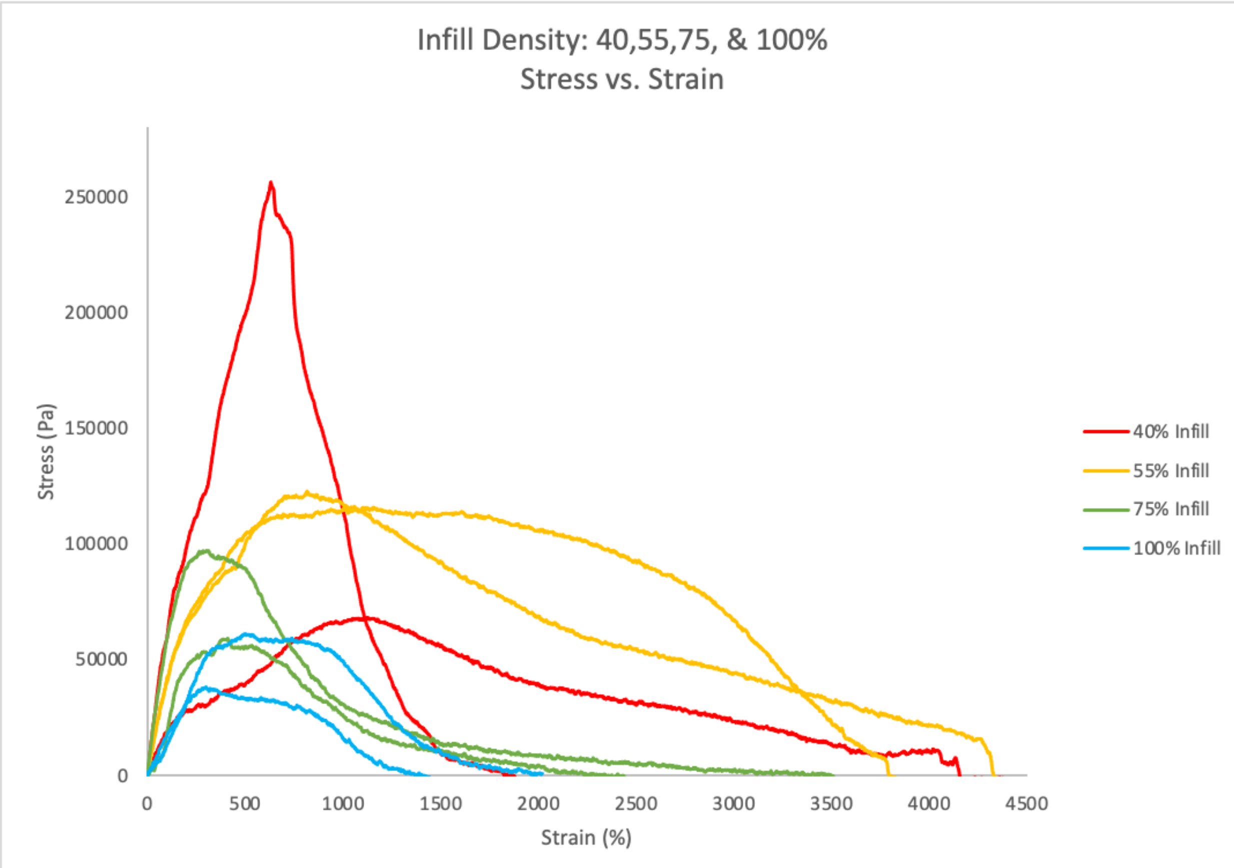


Figure 7. *Infill Densities: 40% (red), 55% (orange), 75% (green), and 100% (blue)) with multiple trials, stress versus strain graph.*

The temperature was held constant at 300 °F, but the times were calculated to be proportional to the mass. Since the post processing time was proportional to the mass, the bars were comparable. Based on **Table 16,** trial 1 of the 40% infill had the highest Young's modulus meaning it was the most brittle out of all the infill densities, which was expected. The second trial of the 40% infill did not follow the same trend as the first trial. The Young's modulus' were very different as well as the stress vs strain graph in **Figure 7**. This indicates the likelihood of some error during the post-processing time. After the bar was tested, it was tasted by the research team for preliminary evaluation. The first trial had an airy and crunchy texture, while the second trial had a softer texture all around. It was hard to pinpoint why the 40% infill density trials varied so much. Both bars were printed back to back and baked one after the other. There could have been an error with the time the bar was post-processed for. Overall, there were consistent trends with the lower infill densities having a higher Young's modulus and ranging from 2.11 to 9.19 x 10^6 Pa with the low end of the range being 100% and the high end of the range being 40% infill.

Infill Pattern

The third experiment focused on investigating the impact infill pattern had on a bar's mechanical property. Five different infill patterns were tested: zig zag, octet, triangles, concentric, and grid. A bend test was conducted, Young's modulus and maximum stress for each bar was recorded in **Table 17**.

Table 17: *Young's modulus and max stress with the corresponding infill pattern.*

Infill Pattern	Young's modulus (Pa)	Max Stress (Pa)
Zig Zag	**Trial 1:** 12.433 x 10^6 **Trial 2:** 10.08 x 10^6	**Trial 1:** 112331 **Trial 2:** 123319
Triangles	**Trial 1:** 25.94 x 10^6 **Trial 2:** 17.26 x 10^6	**Trial 1:** 109664 **Trial 2:** 80678
Concentric	**Trial 1:** 5.63 x 10^6 **Trial 2:** 12.1 x 10^6	**Trial 1:** 48260 **Trial 2:** 64425
Grid	**Trial 1:** 8.88 x 10^6 **Trial 2:** 11.3 x 10^6	**Trial 1**: 51823 **Trial 2:** 54096
Octet	**Trial 1:** 3.92 x 10^6 **Trial 2:** 4.87 x 10^6	**Trial 1**: 49642 **Trial 2:** 59474

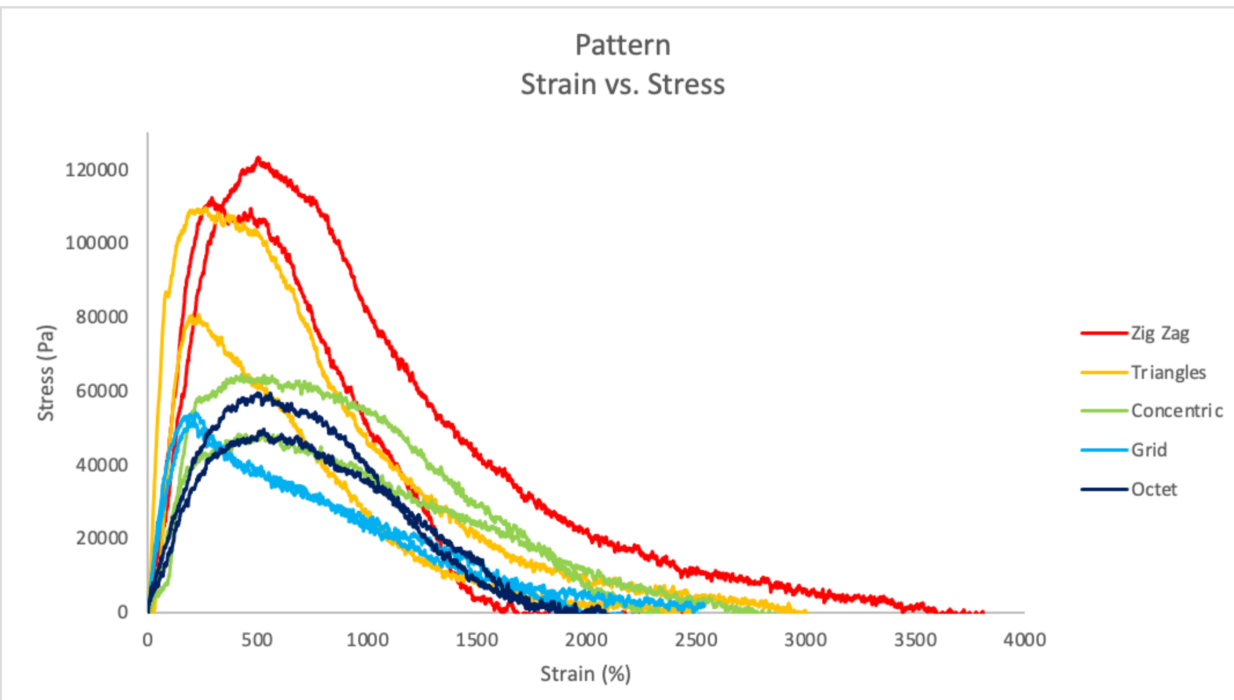


Figure 8. *Infill Patterns (zig zag(red), triangles(orange), concentric(green), grid(blue), octet(indigo)) with multiple trials, stress versus strain graph.*

The Young's modulus was calculated by taking the slope of the strain vs stress curves for each infill pattern. The infill pattern with the greatest Young's modulus was triangular with a value of 25.94 x 10^6 Pa. Although the zig zag pattern had a higher max stress, the slope of the triangle pattern was steeper, meaning that the triangle pattern was stiffer than the zig zag pattern. This is confirmed by the Young's modulus values seen in **Table 17**. **Figure 8** displays all the strain vs stress curves for both trials of every infill pattern. The order of patterns from stiffest to most elastic were: triangle, zig zag, grid, concentric, and octet. This order was expected because the triangles pattern was very complicated and consisted of many lines overlapping each other. The zig zag pattern had one of the least amounts of open spaces between lines. The zig zag pattern was printed at 45-degree angle for the first layer and then in the opposite direction for the second layer; it alternated until it printed all layers. The alternating directions provided the bar with support for the mechanical strength test. It was expected that the octet would have the lowest Young's modulus as it had the greatest visible holes. Octet did not have alternating layers, and there was minimal cross-linking to provide extra strength.

Pilot Consumer Rating Study

The pilot taste test study was conducted with nine participants. The pilot study consisted of four iterations, each time changing parameters slightly based on responses to improve the overall score. In **Table 18**, columns one and two display each iteration tested with their certain specification. The third column represents the number of participants that received each iteration. The last column represents the average overall score out of 6.00. The dimensions of the layers were kept constant for all taste test studies.

Table 18. *Taste-test iteration specifications*

Iteration	Specification	Participants	Average Overall Score (out of 6.00)
1	**Layer 1:** 300°F, 18 min, 100% infill **Layer 2:** 100% infill **Layer 3:** 40% infill	1	3.00
2	**Layer 1:** 325°F, 19 min, 100% infill **Layer 2:** 70% infill Layer 3: 40% infill	1	4.00
3	**Layer 1:** 300°F, 23 min, 100% infill **Layer 2:** 70% infill **Layer 3:** 40% infill	3	5.33
4	**Layer 1:** 300°F, 25 min, 100% infill **Layer 2:** 70% infill **Layer 3:** 40% infill	4	5.00

Overall, as the post processing time or temperature increased, so did the overall score. In the first iteration, the participant gave low scores for texture (2.00) and crunchiness (-3.00). The first iteration was left overnight (around 12 hours) before being tested. Leaving the bar overnight in a sealed container could have impacted the texture of the bar, weakening the structure by locking in moisture. After the first iteration, bars were printed, and taste tested the same day. To address the concerns with crunchiness, the temperature at which the first layer was post processed was increased to 325 F from 300 F. The base layer is the only layer that is post processed, so it could be easily manipulated to change the texture. The post processing time was cut down by a few minutes to ensure the bar would not burn at the higher temperature. The infill of the second layer was also decreased from 100% to 70% to decrease the amount of soft texture in the bar. The second iteration improved the overall score but still scored low in crunchiness (-2.00), meaning the participant wanted a crunchier bar.

In iteration three, the post processing temperature and time were adjusted again to try to achieve a crunchier texture without burning the bar. The temperature was reduced back to 300 °F but the post processing time was increased to 23 minutes in an effort to create a crunchier texture throughout the whole bar. With the new iteration, the overall score increased however, there were still some lower scores for crunchiness and chewiness.

Again, to improve the crunchiness ratings, the temperature was held constant, and the time was increased to 25 minutes. This resulted in increased crunchiness ratings, and two of the four participants rated the crunchiness as "just right." The other two participants rated the crunchiness a -1.0, indicating "slightly too soft." All the other attributes with a scale between -3 and 3, received a score of 0.0 as a mean representing "just right." The other attributes with a rating scale of 1.0 to 6.0 always had a rating of 4.0 and above, indicating many participants were content with the flavors, smell, visual appearance, etc. However, participants consistently reported a greater concern over texture. Overall, iteration four received the best ratings across all categories. Thus, a nutrition label for this iteration was created in consultation with the CCDC SC's senior food technologist, Michelle J. Richardson. See **Figure 9.** See **Figure 10** the full bar prototype for iteration four. The nutrition facts for individual layers can be found in **Appendix I.**

WPI 3D Printed Bar Formulation

Number of Servings: 1 (31.2 g per serving)
Weight: 31.2 g

Nutrition Facts

servings per container
Serving size (31g)

Amount per serving
Calories 110

	% Daily Value*
Total Fat 5g	6%
Saturated Fat 2g	10%
Trans Fat 0g	
Cholesterol 0mg	0%
Sodium 10mg	0%
Total Carbohydrate 14g	5%
Dietary Fiber 2g	7%
Total Sugars 9g	
Includes 6g Added Sugars	12%
Protein 2g	
Vitamin D 0mcg	0%
Calcium 20mg	2%
Iron 0mg	0%
Potassium 93mg	2%

*The % Daily Value tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

Ingredients:

Water, Almond Meal, baking chips, semisweet chocolate, honey, clover, apple, freeze dried, diced, Clover Honey, almond butter, Rolled Oats, applesauce, cinnamon, baking chips, dark chocolate, 53% cacao, morsels, sunflower seed butter, natural, oil, coconut, expeller pressed, organic, IMITATION VANILLA FLAVOR (WATER, PROPYLENE GLYCOL, CARAMEL COLOR, AND ARTIFICIAL FLAVOR), rice cake, apple cinnamon, apple, freeze dried, Ground Cinnamon.

Allergens:

Contains Milk, Soy, Tree Nuts.

Figure 9. *Nutrition facts and ingredients list for full bar prototype, iteration four.*

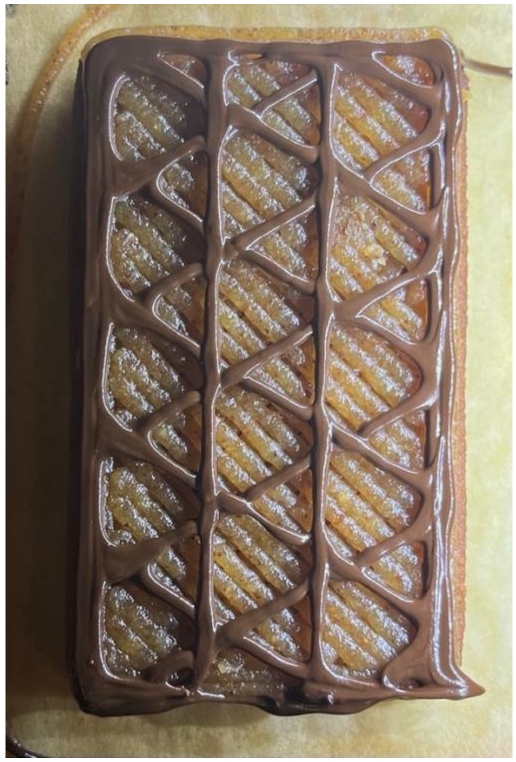


Figure 10. *Iteration 4, full bar prototype used for the pilot taste test study*

None of the participants had ever tried 3D printed food before. Previous work has shown that individuals who have tried 3D printed food are more likely to enjoy 3D printed food on a subsequent occasion [7]. In terms of satiety, 78% of participants said the bar would be satisfying as a snack. On the other hand, only 33% of participants said the bar would be satisfying as a meal replacement if given a larger portion. Since the pilot study was conducted with only nine participants, no clear trends can be identified, besides participants enjoyed a crunchier bar overall. With a greater sampling pool, more conclusions can be drawn.

Potential Sources of Error

When designing the bar formulation, there were many potential sources of error. One used measuring tools like teaspoons, tablespoons, and measuring cups instead of finer instruments measuring in grams and milliliters with higher accuracy. When using these household kitchen measuring tools, there could be greater variability when creating the formulation leading to differences in taste, texture, and viscosity. Another potential source of error arose when initially creating the bar formulation. The oats, chocolate, and freeze-dried apples were food processed, but there was no consistent processing time. This led to large variability in particle size from print to print. By the end of the research, however, the food processing time was consistent to avoid such inconsistencies.

Once the demand for bars increased, the dry ingredients were mixed in larger batches leading to additional potential sources of error. Initially, enough dry ingredients were mixed to create the formulation for one capsule (in the Foodini) or one syringe (in the Hyrel). However, this was inefficient and time consuming to accommodate larger print demand. Therefore, dry ingredients (oats and freeze-dried apples) were pre-mixed to produce 663 grams of base formulation, including the wet ingredients, which is enough material to produce around 24 base bars. A potential source of error with making such a large batch of dry ingredients was that there was no way to ensure even distribution of materials when making smaller batches. The freeze-dried apples and almond flour tended to clump up in the larger scale dry ingredients if not used immediately. If the large clumps of material were not crushed before being used for smaller batches, it could have led to inconsistent amounts of freeze-dried apples or almond flour in the smaller batches.

Several obstacles occurred that impacted efficiency. For example, when the feedstock ran out, more had to be made, which was time consuming and interrupted the printing flow. Another obstacle would be a syringe getting clogged with either apple pieces or chocolate. This was an issue when the formulation had to be adapted from the Foodini to the Hyrel. The Foodini had a heating element that was used to melt the chocolate. Clogs interfered with the time of prints being post processed back-to-back because prints had to be discarded if there were too many pores. Troubleshooting clogged syringes was time consuming since if the syringe got clogged once, it was likely to get clogged again due to an issue with the way the formulation was mixed.

Lastly, there were some potential sources of errors when performing the mechanical bend and compression tests. After the bars were printed and post-processed, they were cooled for at least two hours, but after that, it was hard to regulate how long the bars were exposed to the atmosphere. The time and temperature matrix, with 100% infill and dimensions of 4 x 7 x 0.75 cm, it took about 14 minutes to print. Post processing the bar took between 10 to 25 minutes. In a day, four to six bars were printed before running the bend and compression tests. The MultiTest 2.5-dV(u) was in a laboratory further away from where the bars were being printed. The issue with printing and post processing all the bars before testing them was that the bars printed earlier in the day had been sitting out for longer than the bars that were printed last. Most trials were printed back-to-back of one another, if possible, to avoid as much variability between trials. Ultimately it was not feasible to let the bars rest for the same amount of time before being tested. It is unclear how much of an impact this had on the data. Based on previous prints, letting the bar sit overnight weakened the structure of the bar, producing a soggy and soft texture at a certain time and temperature ranges, so all bars were tested the same day.

Future Studies

3DFP is a new technology with a plethora of areas to explore and research. For this study, 3D printing parameters for the specific formulation were studied to give more insight to the sponsor. Within 3D printing parameters, only infill density and infill pattern were focused on, but there were many parameters not in the scope of the project that would give valuable information. Through research and an interview with the CCDC’s food technologist, Michelle J. Richardson, they are interested in adding additives like protein, caffeine, and vitamins to start. With the consumer rating test, the model followed was simple, but future studies could focus on chewing sensory tests or having different controls within the taste test.

Printing Parameters

There are dozens of printing parameters that have to be considered when 3D printing, the same goes for 3DFP. Ultimaker Cura was used as the slicer software, but there are many other software that can be used. No matter what slicer software is used, slicer settings generally consist of similar parameters. For the scope of this project, we only varied infill density and infill pattern but some other good parameters to vary are wall thickness and see if there is a correlation between increasing wall thickness and mechanical strength. Even within the infill density and infill pattern parameters, another experiment could be where the orientation is manipulated. Another essential printing parameter that can be manipulated is nozzle size. The Hyrel comes with varying nozzle sizes and syringes, so the attachments can be interchanged. Print speed can also be varied and studied. In Repetrel, the two main settings were pulses per microliter and flow multiplier; an experiment can be conducted to find the optimal parameters.

Additives

The leading advantage 3D printed food brings to the food industry is customizability. Individuals have the ability to obtain their nutrient needs almost instantly with this new technology. While the idea of personalizing bars for each individual is exciting, it is simply beyond our research for the scope of this project. Vitamins are vital in the health of a warfighter, especially in the field. 3DFP is a great way to incorporate warfighter's individual vitamin intakes into their own meals. In general, not every warfighter is going to be the same even in the same conditions. For example, if one person needs vitamin C and another person needs vitamin D with 3DFP, they should be able to customize their foods. Unlike traditional foods that are all the same and given to everyone, 3DFP will allow warfighters to include and remove vitamins based on their own health needs. Another reason to customize vitamin intake is for warfighters working in various weather conditions. For example, research shows that vitamin C is useful in heat exhaustion recovery [20]. On the other hand, warfighters in extremely cold weather would benefit from vitamin D, which they might lack due to lack of sun exposure.

The next additive of interest is caffeine, a stimulant for warfighters working overnight shifts. According to a 2008 study from the National Sleep Foundation, "Americans are working more and sleeping less, with the average work-day lasting 9 hours 28 minutes and time in bed only 6 hours 55 minutes. The US military is at particularly high risk for sleep disturbances due to hazardous working conditions, inconsistent work hours, harsh environments, routine exposure to loud noises, and crowded sleeping spaces" [21]. 3DFP will allow warfighters to add the right amount of caffeine for their BMI, so they have enough to stay awake for long nights but not intake more than they need. Conversely, future studies can be conducted for additives to help warfighters sleep. Based on different attributes, people experience sleep differently. A sleep survey sent out to the Millennium Cohort members from 2001-2003 came to some conclusions about sleep behaviors based on outside factors. They found male gender and greater stress were significantly analogous with shorter sleeping time. Those who completed the survey during or after deployment also experienced a tougher time going to sleep or staying asleep. Lastly, personnel who reported mental health symptoms also had a tougher time sleeping or staying asleep [21]. Exploring both sides of additives for sleep and staying up is important because making sure warfighters are alert for their shifts is instrumental to their job performance. But if warfighters are not getting enough sleep regularly, it could impact their wellbeing, mental health, and work performance.

Adding additives in terms of a nutritional bar brings up important considerations. It explores what possible additive(s) to include and how it impacts the taste, texture, viscosity, printing parameters, etc. An interesting area of study could be an experiment investigating the threshold of acceptable amounts of protein, caffeine, or vitamins that can be added to a bar before it becomes unprintable or inedible. The future of this research could be instrumental in studying the hedonic features of MREs. As mentioned in the background, many warfighters do not find MREs appetizing, so finding a good balance with the additives could be important to continue to improve MREs for warfighters.

Consumer Rating Experiments

Lastly, there are many directions in which the sensory and psychological aspects of the study could be further explored and expanded. The consumer rating study completed in this paper was only conducted with nine participants and was done to improve the bar prototype. Future studies could include having a control bar, where the control bar has the same dimensions and ratio of material for each layer, but it is not 3D printed. The participant would be given both bars and asked to answer a series of questions about both bars. A traditionally prepared control bar would show any difference in whether participants enjoyed the bar simply based on flavor or because it is 3D printed. Another study can be giving participants bars with different infill densities or infill patterns to see which texture is preferred. A study can be done using electromyography (EMG) sensors to gain more quantitative data on chewing. EMG sensors work by measuring the electrical signals produced by muscles in the body when moved. The sensors can be placed around the participant's jaw to see the muscle movement when chewing bars with different textures.

Conclusion

In this study, the research team partnered with the U.S. Army CCDC SC to explore 3D food printing and how it can be used to provide warfighters with customized food options based on nutrient needs and texture preferences. A 3D printed three layer energy-dense bar was created, and optimal printing parameters were determined. The first layer consisted mainly of oats and nuts. The second layer was a highly viscous fruit jam-like layer with apple cinnamon flavors. The third layer consisted solely of dark chocolate. A food scientist from the U.S Army CCDC SC determined the nutritional information for each layer and developed a nutrition label for the bar.

Throughout the duration of the project, the team used two different printers. The research team started with the "Foodini." a user-friendly printer similar to most household appliances, to achieve Objective 1 and design the bar formulation. The Hyrel printer was then used to accomplish the other four objectives. This switch was needed because the Hyrel had abilities the Foodini simply did not have. The Hyrel was a traditional polymer printer and allowed the team to manipulate the printing parameters. For each printer, optimal printing parameters were determined.

Texture modifications of the bar were conducted by varying post-processing conditions. 28 different post-processing conditions were evaluated. As hypothesized, increasing temperatures increased the bar Young's modulus and maximum strength. The results also confirmed that increasing the duration of post-processing increases the Young's modulus and maximum strength. While there were a few inconsistencies at certain conditions, the data largely followed the trend. This trend of increasing mechanical strength when increasing post-processing conditions was visualized in **Table 13**, where a color gradient can be seen in the images of all 28 samples corresponding to doneness. A viability evaluation was also conducted, viable Young's modulus ranges were found for each temperature interval. At 275°F, the only viable Young's modulus was 11.74 x 10^6 °F, the viable range was between 1.26 x 10^6 to 16.3 x 10^6Pa. At 325°F, the viable range was between 2.77 x 10^6 to 12.5 x 10^6 Pa. Lastly, at 350°F, the viable range was between 13.54 x 10^6 to 28.17 x 10^6 Pa. The maximum load needed to compress a bar 3 mm was compared to the human bite force of 285 N. It was determined that the bite force was much more, implying the bar would be easy to chew.

Texture modifications of the bar were also conducted by varying printing parameters (infill density and infill pattern) that impacted the interior structure of the bar. Four different infill densities were tested, and it was determined that lower infill densities produced higher Young's modulus. Excluding some inconsistencies, the data corresponds to the expected trend. Five different infill shapes were tested. The order from stiffest to softest bar was for infill patterns: triangles, zig zag, grid, concentric, and octet. The highest to lowest maximum stress order was zig zag, triangles, concentric, grid, and octet. The patterns with higher max stress were not necessarily the pattern with the steeper strain vs. stress slope.

A pilot consumer study was conducted to gauge consumer rating/perception of the 3D printed bar. The study consisted of a total of 9 participants and 4 iterations. After each iteration, the rating of the bar increased, resulting in a final average rating of a 5 out of 6—overall, a good response from participants who have never tried 3D printed food. Further exploratory studies include the addition of additives, control bars, and chewing sensory tests.

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Appendix

Appendix A: Layer 1-3 Ingredients and Nutrition Facts
Layer 1
Quaker Oats 100% Whole Grain Oats Old Fashioned

Good & Gather Blanched Almond Flour

Whole Foods 365 Organic Ground Cinnamon

Good & Gather Semi-Sweet Chocolate Chips

ONETANG Freeze-Dried Apple Pomme Lyophilisee

Nutrition Facts

15 servings per container

Serving size	1 package (10g)
Amount per serving **Calories**	**35**
	% Daily Value*
Total Fat 0g	0%
Saturated Fat 0g	0%
Trans Fat 0g	
Cholesterol 0mg	0%
Sodium 0mg	0%
Total Carbohydrate 9g	3%
Dietary Fiber 1g	4%
Total Sugars 8g	
Includes 0g Added Sugars	0%
Protein 0g	
Vitamin D 0mcg	0%
Calcium 0mg	0%
Iron 0.1mg	0%
Potassium 85mg	0%

* The % Daily Value (DV) tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

Ingredient: Apple.
Ingrédient: Pomme.
Storage Condition:
Keep away from direct sunlight and store in a cool and dry place. Please consume as soon as possible after opening.
Condition de stockage:
Tenir à l'abri de la lumière directe du soleil et conserver dans un endroit frais et sec. A consommer dès que possible après ouverture.

Product of China
Produit de Chine
Best Before / Meilleur avant:

Carrington Farms Organic Coconut Cooking Oil Unflavored

Good & Gather Clover Honey: Pure Honey, U.S. Grade A

Poland Spring Water

SunButter Natural Sunflower Butter

Pics Imitation Vanilla Flavor

Layer 2
Quaker Oats 100% Whole Grain Apple Cinnamon Rice Cakes

Nutrition Facts

About 14 servings per container
Serving size 1 cake (13g)

Amount per serving
Calories 50

	% Daily Value*
Total Fat 0g	0%
Saturated Fat 0g	0%
Trans Fat 0g	
Polyunsaturated Fat 0g	
Monounsaturated Fat 0g	
Cholesterol 0mg	0%
Sodium 0mg	0%
Total Carbohydrate 11g	4%
Dietary Fiber 0g	0%
Total Sugars 3g	
Includes 3g Added Sugars	6%
Protein less than 1g	
Vitamin D 0mcg	0%
Calcium 0mg	0%
Iron 0.2mg	0%
Potassium 30mg	0%

* The % Daily Value (DV) tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

Good & Gather Blanched Almond Flour

ONETANG Freeze-Dried Apple Pomme Lyophilisee

Nutrition Facts

15 servings per container

Serving size 1 package (10g)

Amount per serving

Calories	35
	% Daily Value*
Total Fat 0g	0%
Saturated Fat 0g	0%
Trans Fat 0g	
Cholesterol 0mg	0%
Sodium 0mg	0%
Total Carbohydrate 9g	3%
Dietary Fiber 1g	4%
Total Sugars 8g	
Includes 0g Added Sugars	0%
Protein 0g	
Vitamin D 0mcg	0%
Calcium 0mg	0%
Iron 0.1mg	0%
Potassium 85mg	0%

* The % Daily Value (DV) tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

Ingredient: Apple.
Ingrédient: Pomme.
Storage Condition:
Keep away from direct sunlight and store in a cool and dry place. Please consume as soon as possible after opening.
Condition de stockage:
Tenir à l'abri de la lumière directe du soleil et conserver dans un endroit frais et sec. A consommer dès que possible après ouverture.

Product of China
Produit de Chine
Best Before / Meilleur avant:

Mott's Cinnamon Applesauce

Good & Gather Clover Honey: Pure Honey, U.S. Grade A

Good & Gather Creamy Almond Butter: Unsweetened, No Salt Added

Layer 3
Nestle Toll House Dark Chocolate Morsels

Appendix B: Foodini Advanced Printing Parameters

Table 17. *Foodini advanced printing parameters*

Print/Advanced Settings	Range	Units
Nozzle	0.5- 10	mm
Print Speed	200-5000	mm/min
Ingredient Flow Speed	0.1-50	
Fill Factor	0-2	%
First Ingredient Hold	0-20	mm
First Layer Nozzle Height	0-100	mm
Ingredient Height	0-10	mm
Min. Hold Distance	0-200	mm
Preheat Time	0-1000	sec
Line Thickness	0.4-10	mm
Turning Speed Factor	0-1	
Distance Between Layers	0.4-50	mm
First Ingredient Flow	0-50	mm
First Layer Speed	0-100	%
Jump Height	0-20	mm
Resume Ingredient Flow	-2-2	mm
Preheat Temp	0-85	Celsius
Ingredient Flow Temp	0-85	Celsius
Edit Image Preview Settings	**Range**	**Units**
Height (Layers)		
Position		
Fill (ON/OFF)		
Concentric (ON/OFF)		
Number of shells		
Print Preview Settings	**Range**	**Units**
Surface height		
Special nozzle height		
Multiple copies		
Size		

Appendix C: Ultimaker Cura Custom Settings for Layer 1

Table 18. *Ultimaker Cura custom settings for Layer 1 used in Objective 3*

Print Profile Settings	Value	Units
Layer Height	1.2	mm
Initial Layer Height	1.2	mm
Wall Thickness	2	mm
Wall Line Count	1	
Horizontal Expansion	0	mm
Top/Bottom Thickness	0.8	mm
Top Thickness	4	mm
Top Layers	0	
Bottom Thickness	0.8	mm
Bottom Layers	0	
Infill Density	100	%
Infill Pattern	Zig Zag	
Printing Temperature	0	C
Print Speed	30.00	mm/s
Enable Retraction	TRUE/FALSE	
Z Hop When Retracted	TRUE/FALSE	
Enable Print Cooling	TRUE/FALSE	
Generate Support	TRUE/FALSE	
Build Plate Adhesion Type	Skirt	
Skirt Line Count	1	

Appendix D: Repetrel Printing Settings

Hyrel Printer Settings		
Extruder (SDS-60 XT)	**Value**	**Units**
Nozzle Diameter	1.5 mm	mm
Layer Z in mm	0.3	mm
Temp Info		
Print Temp	0	
PwrFactor	100	
Safe Operating Limits Min-Max	0-0	
Overrides		
Pluses/uL	31	
Flow Multiplier	4	
Prime		
Steps	250	
Rate	8000	
Time	150	
Unprime		
Steps	100	
Rate	10000	
Time	-150	
Offsets		
X	0	
Y	0	
Z	0	
Head Info		
Model	SDS-60	
RTD Type	No RTD	

Appendix E: Protocol for Printing Layers 1-3 in Hyrel Engine (SR) with a 1.5 mm Nozzle

Layer 1: Base Layer
Ingredients

1. Quaker Oats 100% Whole Grain Oats Old Fashioned
2. Good & Gather Blanched Almond Flour
3. Whole Foods 365 Organic Ground Cinnamon
4. ONETANG Freeze-Dried Apple Pomme Lyophilisee
5. Poland Spring Water
6. Carrington Farms Organic Coconut Cooking Oil Unflavored
7. Good & Gather Clover Honey: Pure Honey, U.S. Grade A
8. SunButter Natural Sunflower Butter
9. Pics Imitation Vanilla
10. Good & Gather Semi-Sweet Chocolate Chips

Equipment

1. Microflex Cobalt Nitrile Gloves
2. Sani professional no-rinse sanitizing multi-surface wipes
3. Medium glass bowl
4. Cuisinart Food Processor
    1. Model: ECH-4, 120V 60Hz 250W
5. Stainless Steel sieve (1mm size hole sizes)
6. Target: Made By Design
7. All-Clad silicone and stainless steel spatula
8. Hyrel Engine SR
9. All-Clad Toaster oven
10. Baker's Signature 5x5 parchment paper sheets
11. All-clad stainless steel T106 Turner, 13-inch
12. 60 mL plastic syringe
13. Analytical balance

Procedure:

1. Clean work station with the multi-surface wipes to kill any germs or foodborne pathogens.
2. Rinse and wash glass bowl, spatula, turner, stainless steel sieve, and food processor
3. Put on gloves for food safety and to keep hands clean.
4. Weigh out the following dry ingredients (old fashioned oats, almond flour, and cinnamon) on the analytical balance.
5. Add the almond flour and powder cinnamon into the glass bowl
6. Place old fashioned oats in the Cuisinart Food Processor
7. Shut the container properly to be in the locked position
8. Hold the "Grind" button for 30 seconds, pause for 10 seconds and shake a bit to get material off the walls. Press the "Grind" button for another 15 seconds.
9. Sieve the oats through in the glass bowl and discard any larger chunks.
10. Repeat steps 5-8 with the freeze dried apples until the desired mass is acquired
11. Mix the dry ingredients with the silicone spatula until all ingredients are well mixed.

12. Weigh out the following wet ingredients: water, coconut oil, honey, sunbutter, and vanilla extract.
13. Add the wet ingredients to the bowl with dry ingredients and thoroughly mix ingredients with silicone spatula. until it thickens up a little.
14. Lastly weigh out the necessary chocolate, using a double boiler system, melt the chocolate and add to the bowl. Mix thoroughly until homogeneous
15. Place the feedstock in a 60 mL syringe with the spatula, manually purge to get rid of any air bubbles to the 40 mL marker.
16. Weigh and record the mass of two 5x5 parchment paper. Tape the parchment paper in the center on all four corners. Then tape another piece of parchment paper right on top of the other one.
17. Preheat the toaster oven to desired temperature and time.
18. Once the bar is done printing, take the tape off for the top parchment paper and use Turner to transfer the printed part to the toaster oven once preheating is complete.
19. Post process at the desired conditions

Layer 2: Fruit Layer
Ingredients

1. Quaker Oats 100% Whole Grain Apple Cinnamon Rice Cakes
2. Good & Gather Blanched Almond Flour
3. ONETANG Freeze-Dried Apple Pomme Lyophilisee
4. Mott's Cinnamon Applesauce
5. Good & Gather Clover Honey: Pure Honey, U.S. Grade A
6. Good & Gather Creamy Almond Butter: Unsweetened, No Salt Added

Equipment

1. Microflex Cobalt Nitrile Gloves
2. Sani professional no-rinse sanitizing multi-surface wipes
3. Medium glass bowl
4. Cuisinart Food Processor
    1. Model: ECH-4, 120V 60Hz 250W
5. Stainless Steel sieve (1mm size hole sizes)
    1. Target: Made By Design
6. All-Clad silicone and stainless steel spatula
7. 60 mL plastic syringe
8. Baker's Signature 5x5 parchment paper sheets
9. All-clad stainless steel T106 Turner, 13-inch

Procedure

1. Clean work station with the multi-surface wipes to kill any germs or foodborne pathogens.
2. Rinse and wash glass bowl, spatula, turner, food processor, and 1.5mm nozzle
3. Wear gloves for food safety
4. Take 1 apple rice cake, break it up and place it in the Cuisinart Food Processor.
5. Shut the container properly to be in the locked position

6. Hold the “Grind” button for 30 seconds, pause for 10 seconds and shake a bit to get material off the walls. Press the “Grind” button for another 15 seconds.
7. Sieve the apple cinnamon rice cake in the glass bowl and discard any larger chunks until the desired mass is acquired.
8. Repeat steps 4-7 with the freeze dried apples until the desired mass is acquired
9. Weigh out the following ingredients: almond flour, apple sauce, honey, and almond butter
10. Add all the ingredients to the glass bowl, and thoroughly mix ingredients with the silicon spatula until thick consistency.
11. Place the feedstock in a 60 mL syringe with the spatula, manually purge to get rid of any air bubbles
12. Once the first layer has cooled down for at least 30 minutes, line up both parchment papers and tape back on
13. Z calibrate the printer and print second layer on top of the first layer.

Layer 3: Chocolate Drizzle
Ingredients

1. Nestle Toll House Dark Chocolate Morsels

Equipment

1. Microflex Cobalt Nitrile Gloves
2. Sani professional no-rinse sanitizing multi-surface wipes
3. Cuisinart Food Processor
    1. Model: ECH-4, 120V 60Hz 250W
4. All-Clad silicone and stainless steel spatula
5. Hyrel Engine SR
6. 60 mL plastic syringe
7. Baker’s Signature 5x5 parchment paper sheets

Procedure

1. Clean work station with the multi-surface wipes to kill any germs or foodborne pathogens.
2. Wear gloves for food safety.
3. Rinse and wash spatula, food processor, and 1.5mm nozzle
4. Weigh out chocolate
5. Using double boiler system, melt to temperature of (50-55C)
6. Add melted chocolate to a 60 mL plastic syringe. Purge manually to get any air bubble out before printing
7. Calibrate printer and print
8. No post processing is necessary

Appendix F: Taste-test script

Meet the participant in the hallway outside the SEED Lab. Lead the participant to a computer work station in one of the testing rooms in the SEED Lab. Make sure you enter through the testing room door, and not through the wetlab. Enter the participant's ID number in Qualtrics.

Hi, my name is (YOUR NAME) and I am the researcher who will be working with you today. Please excuse my reading off of a script, but I have to make sure everyone receives the same information about this study. First, I just need to go over a few guidelines for your participation. Before we begin, I need you to read over this informed consent document and then I will briefly go over it with you before we sign it. Please let me know if you have any questions.

Click on the consent form on Qualtrics on the computer to the participant, and wait for them to read it.

As you read, I will tell you about our study. We're interested in how we can use 3D food printing technology for various real-world applications. We want our food products to taste good and have nutritional benefits as well, which is why we need your help. In this study, you will be given a 3D printed food product and asked to complete a taste test. Then, you will fill out a questionnaire about 3D food printing in general. Finally, you will answer some brief questions about yourself. Do you have any questions about this?

Pause and wait for any questions to come up. Answer any questions the participant has.

To confirm your consent to participate, please select "I agree to participate in this research."

If the participant DOES NOT consent to participate, thank them for coming and lead them out. Return all forms to the folder and use that study folder for the next participant.

Great! Thank you for agreeing to participate. Now we will get started with the study. We will have a ten-minute long taste-test session where you will complete a taste-test of a 3D food product. I am going to go get the food product that you will be tasting.

Go into the wet-lab and get the 3D food product, and bring it back to the participant. Hand the participant a taste-test form.

As I mentioned, you will complete a taste-test of a 3D printed food product using this form. Please taste as much as you'd like of the 3D food product so that you can accurately rate it. While you're trying the food product, please fill out this rating form. Once you're finished with this rating, you are welcome to eat as much as you want of the remaining food, but please do not change your initial ratings. You do not have to eat the entire product, but please eat enough to answer the questions. You'll have ten minutes to do this task. As you can see on the form, questions 1 & 2 should be answered before you start eating. When I leave the room, you may take off your mask. After ten minutes, I will knock on the door and you can put your mask back on before I re-enter the room. If you need anything, just knock on the door.

Leave the testing room and close the door. Set a timer on your phone for ten minutes.

After ten minutes, return to the testing room.

Knock on the door so the participant can put their mask on.

Ok, you're finished with the first task. Please wait a moment while I get you set up for the next questionnaire.

Collect the taste-test survey form from the participant. Click through the Qualtrics survey to questions about 3D food printing & demographics. Remove the plate with the 3D food product.

Please take as much time as you need to fill out the questionnaire. I'll be in the other room while you do this, but just knock if you have any questions, and also please knock on the door when you're done.

Leave the testing room and close the door. While you wait, measure how much of the 3D food product was consumed by the participant. You can also grant study participation credit on Sona.

Once the participant knocks on the door, return to the testing room. Make sure they have completed the entire Qualtrics survey and the "thank you" filler screen is showing.

The last thing we have to do is take your height and weight. We will go into the back room to do this.

Lead the participant into the wetlab. Make sure no-one else is in the room when taking their height and weight.

Please take off your shoes and stand on the scale so I can measure your height.

If the participant is wearing a very heavy jacket, have them remove that as well.

Record the height on the study log. Be precise about the number of inches.

Please remain on the scale for another moment while I get it to balance to measure your weight.

Move the weights until the scale is perfectly balanced and stable. Record the weight on the study log.

Great, all done. You can put your shoes back on, and we'll head back into the other room.

Lead the participant back into the testing room. Enter their height and weight into Qualtrics.

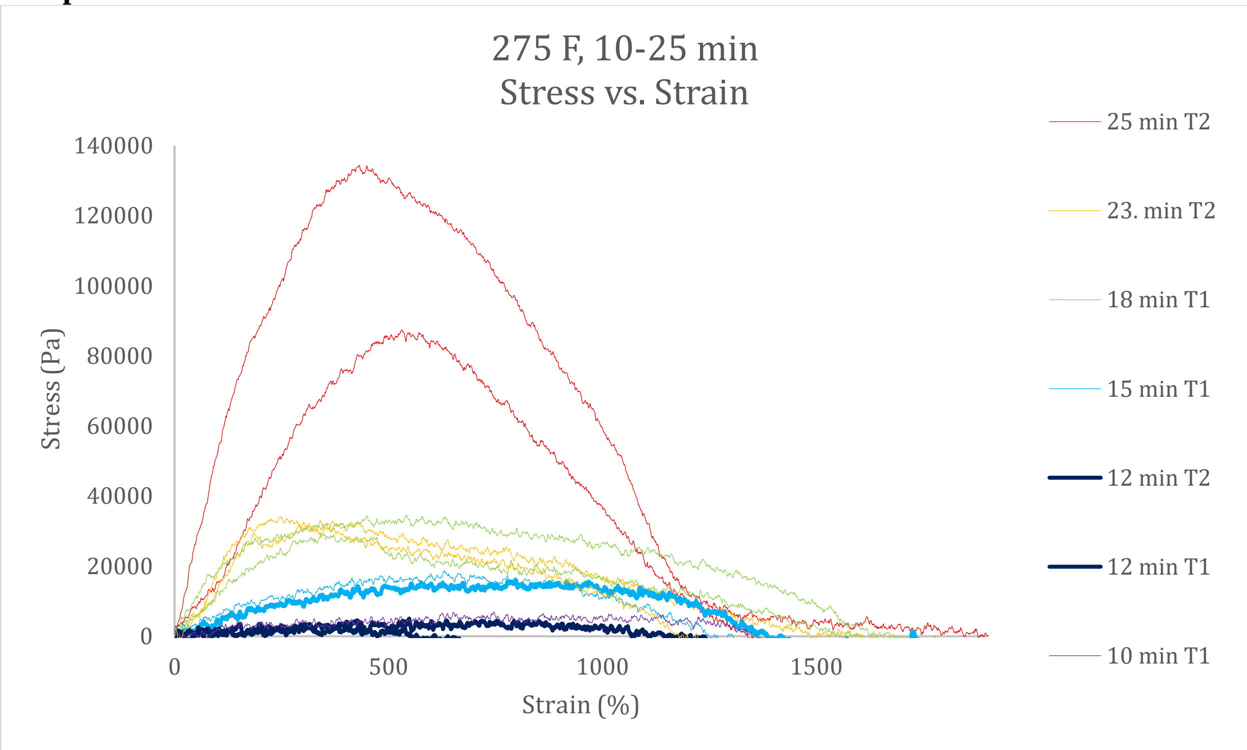
Thank you for participating in our study. Please read through the debriefing form in front of you. If you have any further questions about the purpose of the study or the questions you just answered, please don't hesitate to contact the investigator a [email]

You may wish that we do not include your results and responses in the study data. You have already earned credit for participation in this study and will not lose that credit if you choose to remove your data from the study. If you prefer to have your data removed from the study, please let me know now.

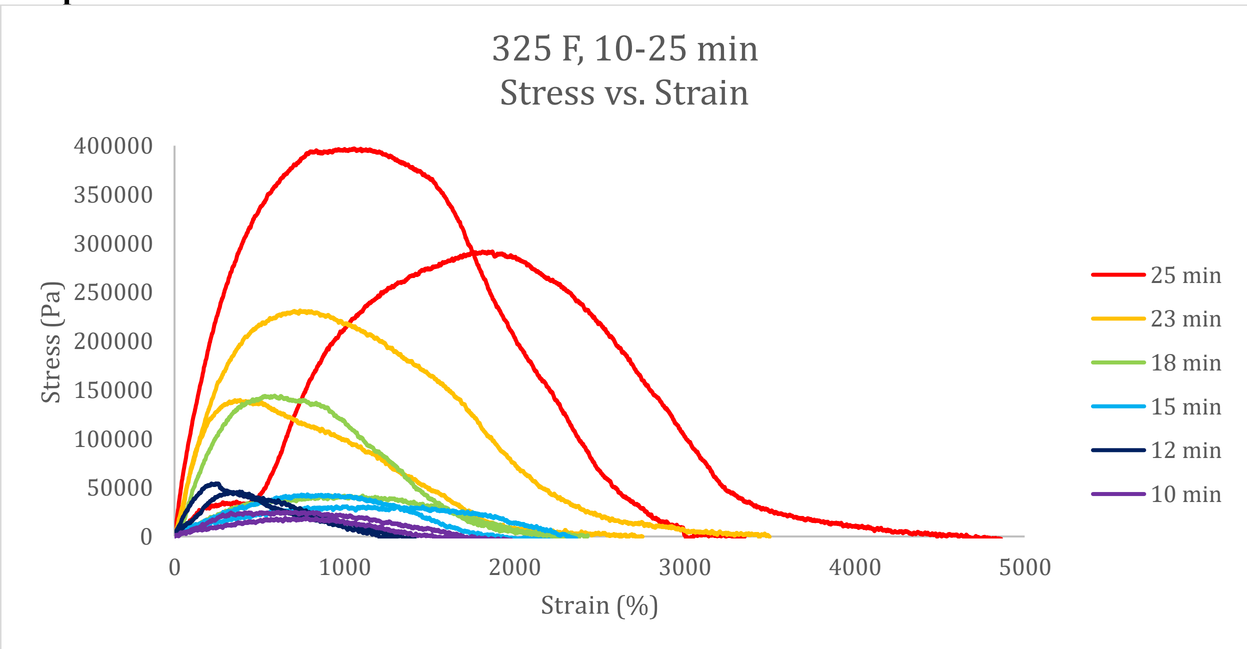
In Qualtrics, select YES if we CAN use data and NO if we CANNOT use the data.
Great. I've already assigned you research credit. Thank you so much for coming in and have a great day!

Appendix G: Stress verse Strain at Constant Temperatures and Varying Times

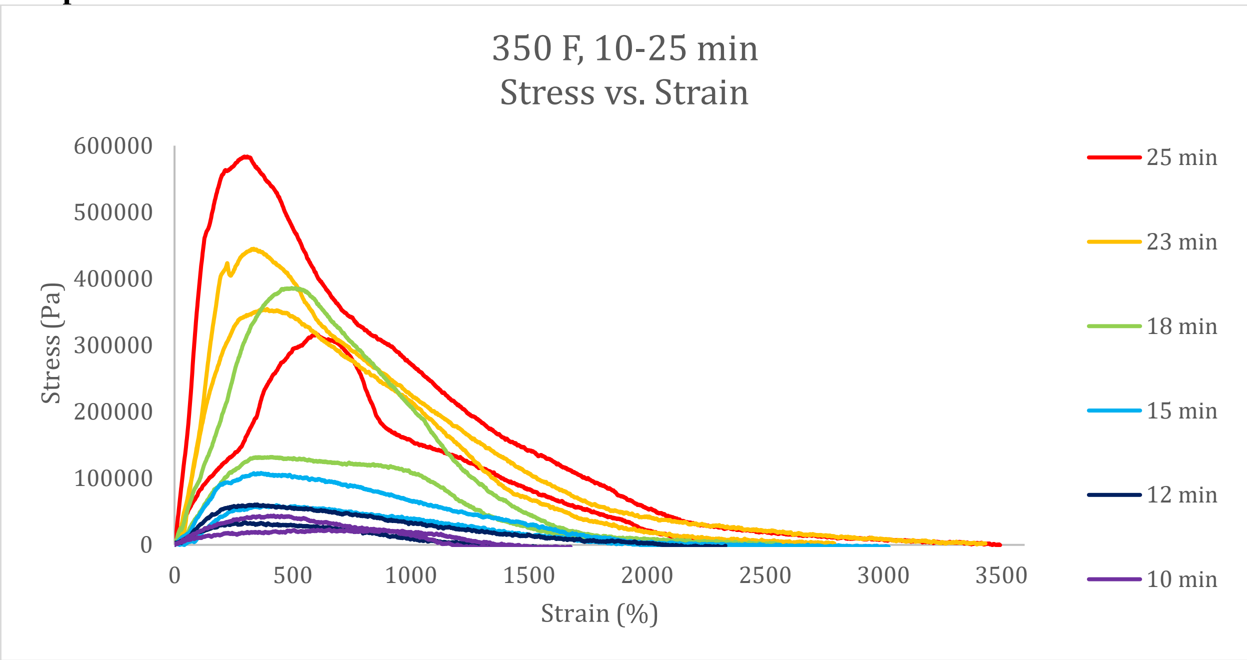
Temperature 275 °F at 10-25 minutes:



Temperature 325 °F at 10-25 minutes:



Temperature 325 °F at 10-25 minutes:



Appendix H: Time versus Temperature Comment Table

Table 19. Research team taste comments on all the bars in time versus temperature matrix

Baking Temperature: 275F					
10min	12min	15min	18min	23min	25min
-already was bending when we put it on the two point -very week Trial 2 had a bend in it already when placed on there -super weak -completely raw on the bottom -feels like eating raw base material in the shape of a bar -stays stuck in teeth -consistency of fudge	-Already bending when placed on the machine -very soft to pick up barely holds togeher -very raw, one texture no crunch whats so every -stays in mouth -very soggy	very soggy -stays in mouth -very raw -all one texture	-completely raw in the center, held up for the bend test, stays in mouth, light in color, moist, can taste the sun butter a lot -edges are a little more cooked the everywhere else but besides that is pretty raw it stays in the mouth for a while and same texture all around	Very raw, taste like the batter before it's baked Only the top layer was slightly baked -edges have a little crunch and different texture than the rest -first few layers were baked on the bottom and top but middle was completely raw	-edges are cooked all the way through but the center is very soft -trial 2 is a little stronger cuz it has more texture on the top
Baking Temperature: 300F					
10min	12min	15min	18min	23min	25min
raw all around -really soft -holds up for the bend test at least no bend in the middle -good flavor -baked the bottom and top layer and everything else is raw -taste like refrigerated batter	-already has a crack on the bottom for Trial 1 but data was pretty close. -Taste pretty raw for the second trial because it has been sitting for less time and trial 1 taste a little more cooked. Both have	-edges are little crunchy but the center and rest of the bar raw and stays in mouth -very raw stays in mouth for a while	-chewy in the middle -a little crunch to the edges not too much -stay in your teeth a little bit	-sturdy and crunchy all around the edges but center is still soft but not unappealing because doesn't stay in mouth -Edges aren't burnt but crispy -Maybe slightly too soft in the	-great flavor -starting to get a little burnt on the bottom and the edges -crispy edges and all cooked throughout the bar -center all cooked through

	great flavor jsut too raw and stays stuck in teeth a bit			center but it has been sitting out for 2 hours which isn't long -Good flavor too -seemed like it already had a crack in it so slightly lower load	
Baking Temperature: 325F					
10min	12min	15min	18min	23min	25min
-was already bending as soon as it was placed on the two points of the bend machine -it was soft when you picked it up -completely raw throughout the whole bar -stays in mouth and sticks to teeth a little -was sitting for 11 hours before conducting bend test	-really soft center -but better texture inside that wasn't completely raw than the 10 mins -stays in mouth and little in teeth -corners were sturdy and had a little bit more bite to it	-soft bottom -really raw soft texture on the inside -edges are a little harder but not crunchy -stays in mouth for a bit	T1 has a small crack at the bottom already so might break sooner than T2 Bottom is a little burnt Center is a little soft The corners and def harder and a little crunchy T2 a lot softer bc fresh batter that was soft, edges are hard not super crispy Bottom is still burnt	-edges are burnt -center is cooked all the way through -great flavor beside burnt edges	-burnt all around the edges -center is soft -extremely hard to bite and chew corners -center is hard to bite into
Baking Temperature: 350F					
10min	12min	15min	18min	23min	25min
-golden bottom -really soft all-around texture	-raw center but the edges have a a little bit more crunch than	-soft texture for almost all the bar but a little bit more baked and held together	-great texture, ends are dark but don't taste too burnt, overall, pretty good. Not too	Not as strong flavor, burnt at the bottom and edges, burnt taste in the edges,	Trial 1: big air bubble/gap at the bottom of the bar

-raw in the center -corners have a slight crunch but not much Trial 2: -same as above but just overall really soft texture	350 for 10 mins. -soft texture overall -tend to stay in the mouth for a while	than the 10 or 12 min. - the corners have a little crunch to them but would want it to be crunchier -but the edges are little dark -would be worried that the middle wouldn't be cooked, and the edges were burnt	crunchy but doesn't melt in mouth. Great flavor -not bad overall -edges are too crunchy and burnt flavor at the end	hard to bite into and chew at points, almost to the cracker texture.	which effected the bend test data Brunt all over the edges appearance wise Very dark in color except the middle Very burnt edges hard to eat Very compact a little softer center but burnt bottom Trial 2: had a small crack in it before doing bend test but otherwise perfect print

Appendix I: Nutrition Label for Layers 1-3

Layer 1:

WPI 3D Layer 1 Formula

Number of Servings: 2 (44.24 g per serving)
Weight: 88.49 g

Nutrition Facts

servings per container	
Serving size	**(44g)**
Amount per serving	
Calories	**140**
	% Daily Value*
Total Fat 7g	**9%**
Saturated Fat 3g	**15%**
Trans Fat 0g	
Cholesterol 0mg	**0%**
Sodium 10mg	**0%**
Total Carbohydrate 19g	**7%**
Dietary Fiber 2g	**7%**
Total Sugars 12g	
Includes 8g Added Sugars	**16%**
Protein 3g	
Vitamin D 0mcg	0%
Calcium 18mg	2%
Iron 1mg	6%
Potassium 119mg	2%

*The % Daily Value tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

Ingredients:

Water, baking chips, semisweet chocolate, honey, clover, apple, freeze dried, diced, Almond Meal, Rolled Oats, sunflower seed butter, natural, oil, coconut, expeller pressed, organic, IMITATION VANILLA FLAVOR (WATER, PROPYLENE GLYCOL, CARAMEL COLOR, AND ARTIFICIAL FLAVOR), Ground Cinnamon.

Allergens:

Contains Milk, Soy, Tree Nuts.

Layer 2:

WPI 3D Layer 2 Formula

Number of Servings: 1 (8.4 g per serving)
Weight: 8.4 g

Nutrition Facts

servings per container

Serving size	**(8g)**
Amount per serving	
Calories	**30**
	% Daily Value*
Total Fat 1.5g	**2%**
Saturated Fat 0g	**0%**
Trans Fat 0g	
Cholesterol 0mg	**0%**
Sodium 5mg	**0%**
Total Carbohydrate 4g	**1%**
Dietary Fiber 0g	**0%**
Total Sugars 3g	
Includes 2g Added Sugars	**4%**
Protein 1g	
Vitamin D 0mcg	0%
Calcium 10mg	0%
Iron 0mg	0%
Potassium 29mg	0%

*The % Daily Value tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

Ingredients:

Clover Honey, almond butter, applesauce, cinnamon, Almond Meal, rice cake, apple cinnamon, apple, freeze dried.

Allergens:

Contains Tree Nuts.

Layer 3:

WPI 3D Layer 3 Formula

Number of Servings: 1 (1.1 g per serving)
Weight: 1.1 g

Nutrition Facts

servings per container
Serving size (1.1g)

Amount per serving
Calories 5

	% Daily Value*
Total Fat 0g	**0%**
Saturated Fat 0g	**0%**
Trans Fat 0g	
Cholesterol 0mg	**0%**
Sodium 0mg	**0%**
Total Carbohydrate 1g	**0%**
Dietary Fiber 0g	**0%**
Total Sugars 0g	
Includes 0g Added Sugars	**0%**
Protein 0g	
Vitamin D 0mcg	0%
Calcium 1mg	0%
Iron 0mg	0%
Potassium 6mg	0%

*The % Daily Value tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

Ingredients:

baking chips, dark chocolate, 53% cacao, morsels.

Allergens:

Contains Milk.