3D Printing Food and the Future of Organic Printing

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Part 1: The History and the Current State of 3D Printing

1A: Definition

"3D printing is already shaking our age-old notions of what can and can't be made."

- Hod Lipson

American robotics engineer, director of Columbia University's Creative Machines Lab

3D printing has emerged as a disruptive technology, revolutionizing traditional manufacturing processes and challenging the status quo. With its ability to create complex and customizable objects, 3D printing has disrupted various industries, ranging from healthcare and aerospace to fashion and automotive. This groundbreaking technology has shattered the barriers of traditional manufacturing, enabling individuals and businesses alike to rapidly prototype, iterate, and produce objects with unprecedented speed and efficiency. By decentralizing production and empowering creativity, 3D printing has opened up new avenues for innovation, transforming how we think about design, manufacturing, and distribution.

At its core, "3D Printing is an additive manufacturing process that creates a physical object from a digital design." (Hayes) By layering materials one on top of another, 3D printers have the power to bring imagination to life, enabling users to create intricate and complex structures with precision and ease. With the ability to produce anything from simple prototypes to intricate medical implants, 3D printing is not just a manufacturing technique; it is a catalyst for innovation and endless possibilities. By understanding the 3D printing process, history, applications, current regulatory environment, and active research and development in the field, we will explore its limitless potential for the future. More explicitly, the future of 3D Printing food and organic material and its ability to promote environmental sustainability and leave a lasting, positive social impact on the world's populations.

1B: International History of 3D Printing

The international history of 3D printing traces its roots back to 1981 in Japan, where Hideo Kodama pioneered the development of a rapid prototyping system (Alexandra). Kodama's innovative approach involved utilizing a layer-by-layer technique for manufacturing, utilizing a photosensitive resin that could be polymerized using UV light. This groundbreaking method, regarded as an early version of the modern Stereolithography (SLA) machine, is often attributed to Kodama as the first inventor of this manufacturing system. His visionary work laid the foundation for future advancements and widespread adoption of 3D printing technology.

However, in the international history of 3D printing, it is crucial to acknowledge that Hideo Kodama's early patent for his groundbreaking manufacturing system was met with rejection. This rejection inadvertently opened the door for the United States to enter the scene and ultimately dominate the 3D printing market. With Kodama's patent not being granted, it allowed American inventors and entrepreneurs to explore and develop their approaches to 3D printing technology. This paved the way for the emergence of significant players like Charles Hull, who went on to invent the Stereolithography Apparatus (SLA) machine, Carl Deckard, who invented Selective Laser Sintering (SLS) for industrial 3D printing, and Scott Crump, who introduced the Fused Deposition Modeling (FDM) technique (these three key US inventors will be reintroduced later when discussing the history of American 3D printing). Ultimately, the absence of Kodama's patent played a pivotal role in enabling the United States to assert its dominance in the field of 3D printing, leading to the rapid growth and global influence of the technology.

In the years following Kodama's contributions and patent rejection, a group of French researchers were also working towards the development of a rapid prototyping machine. Their goal was to create a system that utilized a laser to solidify liquid monomers instead of using resin. Similar to Kodama, they faced difficulties in patenting this technology, but they are acknowledged for their contribution to inventing this system. In conclusion, from Kodama's initial breakthrough, the international community would go on to explore and refine various 3D printing techniques, leading to the extraordinary range of applications and capabilities we witness today. The international history of 3D printing is a testament to the collaborative and innovative spirit of scientists, engineers, and entrepreneurs across the globe, who continue to push the boundaries of this transformative technology.

1C: The US History of 3D Printing

In the United States, the history of 3D printing can be traced back to the early 1980s when Charles Hull, driven by his frustration with the limitations of creating small custom parts for furniture, embarked on developing a system for producing 3D models (Alexandra). In 1981, Hull devised a method that involved curing photosensitive resin layer by layer, which laid the foundation for what would later become known as Stereolithography (SLA) technology. Notably, Hull's work occurred during the same year as Japanese researcher and developer, Hideo Kodama. Both are largely cited as being the creators of SLA technology. Again, as mentioned above, Kodama was unable to earn a patent for his contributions to SLA 3D printing capabilities.

The first successful 3D-printed part, using this SLA method, was created in 1982. Recognizing the potential of this technology, Hull filed a patent for his invention and was successful in getting patent protections for his technology in 1984. By being able to obtain exclusive rights to prevent others from copying, manufacturing, selling, or importing SLA technology and 3D printing abilities, Hull successfully was able to commercially dominate the 3D printing market. Two years later, in 1986, Hull co-founded 3D Systems, which became the world's first 3D printing company. Hull's initial research and development in producing custom parts for furniture led him to the forefront of disruptive innovation and technology.

In 1988, 3D Systems commercialized the SLA-1 Stereolithography (SLA) printer, marking a significant milestone in the history of 3D printing. This breakthrough technology paved the way for the rapid growth and development of the 3D printing industry, revolutionizing manufacturing processes and opening up new possibilities for design, prototyping, and production. The contributions of Charles Hull and the establishment of 3D Systems played a pivotal role in shaping the early history of 3D printing in the United States and beyond.

Notably, Hull's contributions led Carl Deckard, a researcher at the University of Texas, to play a significant role in the advancement of 3D printing technology with his invention of Selective Laser Sintering (SLS) (Alexandra). This groundbreaking technology was patented by Deckard, establishing his exclusive rights to this innovative process. Unlike traditional methods that relied on liquid materials, SLS introduced a new approach by fusing powders using a laser. This process involved selectively sintering layers of powdered material, such as plastics or metals, to create a solid object layer by layer. The laser would selectively heat the powdered material, causing it to fuse and solidify, forming the desired shape.

Around the same time as Deckard was developing, another inventor named Scott Crump patented Fused Deposition Modeling (FDM) (Alexandra). Also known as Fused Filament Fabrication (FFF), this technique differed from SLS and SLA (Stereolithography) by using a different mechanism. Instead of relying on light or lasers, FDM involves the direct extrusion of a filament from a heated nozzle. In FDM technology, a filament made of thermoplastic material is heated to a molten state and then precisely deposited layer by layer to build the desired object. The heated filament solidifies rapidly upon deposition, creating a strong bond between the layers. This patent granted Crump the exclusive right to this innovative method. Over the years, FDM, or Fused Filament Fabrication, has evolved and become the most widely used form of 3D printing. Its simplicity, affordability, and versatility have contributed to its widespread adoption across various industries and applications. Today, FDM technology is commonly employed in diverse fields such as prototyping, manufacturing, education, and even in-home 3D printing. Both SLS and FDM technologies have revolutionized the world of 3D printing, opening up new possibilities for rapid prototyping, manufacturing, and customization. Each method has its unique advantages and applications, contributing to the ever-expanding landscape of additive manufacturing.

The history of 3D printing and its ability to be as disruptive as it is today can largely be accredited to Hull, Deckard, and Crump and their innovative discoveries of SLA, SLS, and FDM applications in advancing 3D printing. However, “these three technologies are not the only types of 3D printing methods that exist. But, they are the three that serve as the building blocks that would lay the groundwork for the technology to grow and for the industry to be disrupted.” (Alexandra) When looking toward the future of 3D printing, it is imperative to consider both how these processes have influenced printing technology and how these processes can be manipulated to spur further development in the space (notably, with food and organic printing).

Expansion of 3D Printing Capabilities

With 3D printing’s ability to produce prototypes quickly (escalating innovation through low-cost and more immediate testing), 3D printing capabilities largely expanded in the last three decades (notably, in both consumer and medical industries as printer capabilities continued to become more efficient). As 3D printing was initially developed by Charles Hull to solve a consumer problem—or, generate customized pieces for furniture—everyday consumers use 3D printing capabilities. In 2005, Dr. Adrian Bowyer invented the RepRap (or, an open-source concept to create a self-replicating 3D printer process). The RepRap Project inspired the development of numerous low-cost 3D printers, democratizing access to 3D printing technology (Fidan). It played a crucial role in expanding the use of 3D printing beyond the manufacturing and research industries and into fields such as architecture and medicine. Meanwhile, in 2008, "Darwin" became the first commercially available 3D printer that was designed under this open-source concept. As 3D printing expanded, it grew from having the ability to produce small, custom pieces of furniture, to being able to produce a livable family home (in 2018, the first family moved into a 3D-printed house).

As consumer applications expand with the rise of 3D printing, so do medical. Moreover, a new form of printing has been developed that encompasses this interdisciplinarity. Bioprinting is an innovative technology that combines 3D printing and biology to create three-dimensional structures made of living cells (Tripathi). Using bio-inks containing cells, growth factors, and biomaterials, bioprinters deposit these materials layer by layer to build complex tissues and organ-like structures. With applications in regenerative medicine, drug discovery, and tissue engineering, bioprinting has the potential to revolutionize healthcare by enabling the creation of personalized tissues and organs for transplantation, disease modeling, and drug testing. Ongoing research aims to enhance bio-ink formulations, printing techniques, and applications, making bioprinting an exciting frontier at the intersection of biology and 3D printing, with the potential to advance personalized medicine. For example, through 3D printing and bioprinting, scientists, researchers, and medical professionals can print human body anatomy, like: organs for transplant surgery (starting in 1999 with Wake Forest's Institute for Regenerative Medicine), miniature kidneys (since 2000), prosthetic limbs (since 2008), prosthetic jaws (since 2012), and bones (since 2016). These applications of 3D printing have fundamentally reshaped the original goals of 3D printing technology, further emphasizing the disruptive nature and transformative potential of 3D printing since its inception.

In fact, in 2013, 3D printing was recognized by former President Barack Obama in his State of the Union address as a major issue for the future (Gross). In his speech, President Obama shared how 3D printing was moving away from being tucked away in labs and research facilities, and was moving into the hands of the American public. The recognition of 3D printing's capabilities was significant because it highlighted the potential of this emerging technology and its economic implications. By acknowledging 3D printing, President Obama focused attention on policy initiatives and increased public awareness of the technology. His recognition also provided inspiration and encouragement to those working in the field, signaling government support for advancements in 3D printing.

As 3D printing has revolutionized the last four decades of innovation within consumer products, medical treatment, and political agendas, it is important to look forward and see which direction its capabilities are heading. The future of 3D printing will continue to revolutionize not only traditional manufacturing processes but also the production of organic materials and even food. As technology continues to advance, researchers and scientists are exploring the possibilities of using 3D printers to create complex structures using organic materials. This breakthrough could have far-reaching implications in fields such as medicine, where 3D-printed organs could potentially address the shortage of donor organs. Additionally, the concept of food printing holds promise for personalized nutrition, sustainability, and addressing global food security challenges. With ongoing advancements and research in this area, the future of 3D printing appears to be heading towards the realm of organic material and food printing.

1E: Regulatory Environment

The FDA does not regulate 3D printers themselves but rather the medical products made via 3D printing. The regulatory review required depends on the type of product being made, its intended use, and the potential risks to patients. Devices produced through 3D printing are regulated by the FDA's Center for Devices and Radiological Health and are classified into different regulatory categories based on risk level. In 2017, the FDA released guidance on the information required for 3D-printed device application submissions. The agency aims to ensure that 3D-printed medical devices are safe, effective, and of high quality for patients (Health Care Products and Team Xometry).

While the 3D printing process requires larger amounts of energy compared to traditional manufacturing methods, causing more emissions, there are currently no specific regulatory oversights on the environmental impact of 3D printing (Health Care Products). The future of 3D printing may see regulatory oversight concerning sustainability measures (similar to how other industries like automobiles or pesticides are regulated).

In terms of food consumption, 3D-printed food is considered safe as long as all ingredients and additives used are FDA-approved, and the printer utilizes food-grade materials for the nozzle, syringe, and base plate. Food-safe 3D printing filaments include PLA, PP, co-polyester, PET, PET-G, HIPS, and nylon-6, among others. However, regulations regarding organic material in 3D printing are less specific.

In summary, the FDA regulates medical products made through 3D printing, ensuring their safety and effectiveness. While there are no specific environmental regulations for 3D printing, the technology may consume more energy and emit more emissions compared to traditional manufacturing methods. Regarding food consumption, 3D-printed food is considered safe as long as FDA-approved ingredients and food-grade materials are used in the printing process. Therefore the lack of regulation in the 3D printing space opens the doors for innovation.

1F: Current Foods Being Printed

Just as the Green Revolution challenged the efficiency of the global food chain and asked questions like where, how much, and what kind of food global populations can consume; 3D printing is again challenging the efficiency of the global food chain. Several types of food are currently being 3D printed, including 3D printed pasta (Barilla), Plant-based steaks (ReDefine Meat), 3D-printed chocolate art (Mona Lisa 3D Studio), Fruit flavor drops for cocktails (Smart Cups), Protein-fortified snack bars (Emminger), Pancake and waffle printers with built-in cooking (PancakeBot), and 3D-printed seaweed snacks (Roberto Lemus' work and Marvel Labs). While there is limited regulation and safety of these specific 3D-printed food items, 3D printing technology has been used to create innovative and customized food products. The regulation of these products would depend on factors such as their ingredients, intended use, and potential risks to consumers. While there are no specific regulations for 3D-printed food, using ingredients that the FDA already recognizes as safe ensures the food is fit for consumption.

Interestingly, as stated earlier the United States largely innovated, scaled, and denominated the early market of 3D printing. However, it is fascinating to see that the key stakeholders in funding large-scale 3D-printed foods are not US-based. Instead, the funding for 3D-printed pasta comes out of research from Barilla in Italy (Wakefield). The funding for 3D-printed meats comes out of research from ReDefine Meat in Israel (Jobs). The funding for 3D-printed protein bars comes out of research from the Nourished company in the UK (Emminger). Whereas startups like Mona Lisa 3D Studio, Smart Cups, and PancakeBot are based in the United States and are not currently disrupting the food industry to the scale that

Barilla, ReDefine Meat, and Nourished are ("MONA LISA 3D STUDIO", Gonzalez, Emminger, and "PancakeBot").

Part 2: Active Research and Development in the Field (Interview Findings)

For a comprehensive look at the current research and development happening in the 3D printing industry, I spoke with three current researchers all engaging with 3D printing and organic material.

At the graduate school level, I spoke with Jack Kraynak: a recent graduate from Temple University. During his time as an undergraduate, Kraynak majored in bioengineering and spent his time researching in a bioprinting lab. He is now pursuing a 3D Printing Master's Degree where he will focus on bioprinting.

At the Post-Doctorate level, I spoke with Dr. Jonathan Blutinger: a current postdoctoral fellow in Hod Lipson's Creative Machines Lab at Columbia University's School of Engineering. Blutinger is currently funded by ReDefine Meat (as referenced above) with a research focus on digital cooking and food modeling.

At the research lab director level, I spoke with Dr. Michael Rivera: the current director of the Utility Research Lab of CU Boulder's ATLAS Program. He oversees a highly interdisciplinary group that invents and investigates digital fabrication technology, tools, and techniques. Rivera is funded by the NSF where his research focuses largely on sustainability and organic printing.

2A: Jack Kraynak

During his time at Temple, Kraynak researched the mechanical aspects of extrusion bioprinting that directly affect the viability and number of cells that die during each 'print'. His work aimed to minimize cell death during extrusion bioprinting using a gelatin-alginate bioink.

Kraynak selected extrusion bioprinting for its accessibility and cost-effectiveness. Ultimately, he researched how factors like different nozzles (cylindrical or conical) and the concentration of the gelatin-alginate bioink can be varied to find the optimal concentration that maintains high cell survivability. By reducing the most efficient combination of specific nozzle and bio-ink concentration, Kraynak suggests that cell damage during extrusion bioprinting can be significantly minimized, improving the quality and viability of the printed structures. This advancement in extrusion bioprinting, with reduced cell death, may lead to increased utilization of the technique by researchers and potentially accelerate the innovation of bioprinting toward the ultimate goal of printing fully functioning organs. His work won the 2021 Temple University Livingstone Undergraduate Research Award in STEM.

From our conversation, I learned a few interesting points beyond learning more of his research. First, the majority of 3D printing research in US academia is focused on bioprinting. The increased funding for the interdisciplinary research of biology with mechanical engineering has led to an increase in bioprinting research. Ultimately, the combination of 3D printing and high-throughput techniques offers advantages in improving product models and reducing manufacturing time, production cost, and time to market which further enhances the ability to recreate the biological properties and functions of human tissues, organs, and circulation. (Mendoza-Cerezo).

Second, and a similar point, to pursue a research program in working with organic material or food development, the academic programs you apply for rely largely on interdisciplinary approaches and applications of 3D printing (thus, this research is largely student-driven). Because 3D printing is still young, the direction in which you use the technology is vast, offering exciting opportunities and potential use cases.

Third, the world of 3D printing—and especially bioprinting—is small. Kraynak worked at 3D Systems, Charles Hull's company (or the original 3D printing company to ever exist). The niche industry of 3D printing research and development promotes healthy competition (incentivizing innovation), can more easily respond to customer demands and emerging trends, and facilitates collaboration. Similarly, all three researchers I spoke with have Pennsylvania connections; an interesting note considering how large the US engineering industry is.

Importantly, while printing food and printing organs have different uses, they are both similar in that they rely on the foundations of bioprinting. While Kraynak's research aims to be applied to the medical field, the work can inevitably be extended to 3D printing food. The concept of increasing cell survival can also be translated to feeding populations safely in food research and development. As bioprinting is the most common form of organic 3D printing, it serves as the stepping stone from mechanical applications of 3D printing to a tangible 3D printed meal. Work from graduate students like Kraynak is invaluable when transitioning applications of 3D printing from plastic products to nourishing meals.

2B: Dr. Jonathan Blutinger

Dr. Blutinger graduated with a BS in Mechanical Engineering from UPenn. Blutinger then went on to get an MSE in Integrated Product Design from UPenn before going to Columbia University where he earned his PhD in Mechanical Engineering. His PhD research focused on using digital lasers in 3D printing to create and prepare food. Blutinger is still at Columbia working as a food robotics engineer postdoc with funding from ReDefine Meat.

I initially came across Dr. Blutinger's work through a @newscientist Instagram post on March 22nd, 2023. Here, the account shared Blutinger's paper, "The future of software-controlled cooking." I was completely fascinated and reached out to Dr. Blutinger asking for an interview. In our conversation, I shared how revolutionizing I found his project to be as it provided a disruptive solution towards food safety (as his food is prepared with less human handling and therefore reduces the risk of food-borne illnesses), food preparation (through customized heating and cooking abilities), and food transparency (by knowing precisely the macro and micronutrients within a meal).

However, in speaking with Blutinger, he directed me to the comments on the Instagram post where I saw things like: “Disgusting,” “Cheesecake looks like a type 6 stool 🤮,” or “Nice gimmick but not the future of nutrition.” Other comments were more elaborate and criticized the 3D printing manufacturing process. Comments were noted as stating: “I’m not impressed because of the obvious error the stupid robot made where the strawberry jam sept out. Humans are still superior!” Or, “And? A) not great ingredients and b) is it for toothless people, all puréed up? Ever heard of actually enjoying the process of making?” or “I like 3D printing. But this is one of the most revolting pieces of ‘nutrition’ I’ve ever seen.”

Reading these comments was shocking. Through my research, I have only a few other researchers and startups engaging with the type of development that is coming out of Columbia’s labs (and in particular, work that is similar to that of Dr. Blutinger). Yet, while being so innovative and disrupting both the current state of 3D printing and the food industry, Dr. Blutinger is met with online trolls and hate comments. Ultimately, this concerns me: if such innovative researchers and developers are met with such negativity, what does that say about public respect for disruptive technology? In our conversations, Dr. Blutinger seemingly shrugged off these comments; he was not concerned with what some random stranger had to say about his research. Instead, Dr. Blutinger was excited that his work sparked a dialogue on the future of how global populations are fed and how food is produced and distributed around the world.

While online trolls are busy criticizing the appearance of his designs, Dr. Blutinger is busy considering the social implications of how 3D printing can make the food industry more accessible, transparent, and safe. In mentioning how 3D printing food brings a level of precision to what food is made out of, individuals with allergies or who track the macro and micronutrients of their diets, are now able to know exactly what they are consuming. With knowledge comes power: therefore, Dr. Blutinger is reimagining the future of food.

Ultimately, the work of Dr. Blutinger reminds me of the George Bernard Shaw quote Professor Toohey shared on the first day of class: “The reasonable man adapts himself to the world: the unreasonable one persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable man.” While online trolls continue to hide behind their screens and criticize innovation, Dr. Blutinger is showing up and putting forth technology that challenges the status quo of the food industry. Dr. Blutinger is an unreasonable man adapting the 3D printing space into an environment that only further proves to be disruptive.

Lastly, in speaking with Dr. Blutinger, I learned more about the sources of funding for 3D printing research. While Dr. Blutinger is funded by an Israeli company (ReDefine Meat), other nations like Sweden and Germany are also funding 3D-printed food research. With less US funding engagement, this is especially interesting to see considering that the US was so active in funding the research and development of 3D printing in its original conception with innovators like Charles Hull (1980s-1990s). However, seeing the comment section of his research online, it becomes clear why the United States is not as innovative as it once was in 3D printing technology: the public does not respect the advancements it once did.

2C: Dr. Michael Rivera

Dr. Mike graduated cum laude with a BSE in Digital Media Design at UPenn. He then went on to get an MSE in Computer Graphics and Game Technology from UPenn where his research focused on 3D printing uses for customized patient care. He then went on to get his PhD in Human-Computer Interaction from Carnegie Mellon University. There, he researched how to use everyday items in 3D printing. Now, after completing his postdoc at CU Boulder, he is the lab director of the Utility Research Lab of Boulder's ATLAS Institute. In this position, he oversees a highly interdisciplinary group that invents and investigates digital fabrication technology, tools, and techniques. Specifically, Dr. Rivera works with undergraduates, graduate students (both masters and PhDs), and postdocs in working towards sustainability in 3D printing.

I initially came across Dr. Rivera's lab through a recent research paper he and his lab at CU Boulder published: "Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds." Here, the research project connects two of Dr. Rivera's passions: finding alternative filaments for 3D printing and sustainability (Rivera). Not only is the material of coffee grounds compostable and recyclable but it can also be easily produced and printed at home; encouraging other 3D printing deverlopers to evaluate the sustainability of their projects. Because I was extremely fascinated by how Rivera and his lab were using organic materials for 3D printed projects, I reached out to Rivera and we discussed the intentions and implications of his research. Moreover, in our initial conversations, I was even invited to visit his lab at CU Boulder. I eagerly accepted the opportunity!

While visiting his lab, our conversations were guided by (1) a deep environmental discussion, (2) a review of his published research throughout the lab, and (3) a sharing of his unpublished work. First, Dr. Rivera emphasized the importance of sustainability within the 3D printing industry. Shockingly, "[3D printing] technology uses larger amounts of energy than milling and drilling machines. And to produce an object of the same weight, the 3D printing process may require 50 to 100 times more electrical energy than standard machines, thereby causing more emissions." ("Is 3D Printing Eco-Friendly & Sustainable?") Ultimately, the goal of Dr. Rivera's lab is to "develop hardware, software, and materials with a purpose—to advance science and engineering while positively impacting people, society, and the environment." ("Utility Research Lab.") Considering that the manufacturing process of 3D printing is so energy intensive, Dr. Rivera is deeply passionate about making the entire technology a more sustainable process to become more mainstream.

While walking around Dr. Rivera's lab, we came across a printer running that was producing a toy castle. Interestingly, as my visit was over Thanksgiving break, no student was monitoring the project and no assignments were due in Rivera's lab for building such a project. Dr. Rivera shared his frustrations with me over this type of development. Even though 3D printing allows the public to get involved with STEM and unleash their creativity, development should be intentional, not wasteful and for display. Here, Rivera and I discussed the environmental consequences of "printing things for the sake of printing." The amount of time, energy, and resources that go into 3D printing should be respected, not abused because one has the privilege to use the technology. The disrespect in appreciating 3D printing and its capabilities suggests that the masses do not view the technology as "disruptive" but as a new capability that is at their disposal. Rivera argues that 3D printing technology must continue to innovate and advance for the public to straddle the fine line between genuine curiosity to use the technology and having the respect to understand the consequences of abusing its technical abilities.

Second, Dr. Rivera shared with me the 3D printer and its corresponding prints from the paper I found online ("Designing a Sustainable Material for 3D Printing with Spent Coffee Grounds"). It was extremely exciting to see the project in real life and feel how strong the coffee material was. According to Dr. Rivera, the compostability of the material allows the prints years of use before it becomes too weak to hold its original structural integrity. Interestingly, Dr. Rivera did reveal to me that he is not as interested in commercializing this technology. Instead, he hopes that this project—and the students associated—will go on and prioritize sustainability within their future research and development. Considering that the U.S. patent system rewards innovation and disruptive technologies through exclusive market access for a limited time, I found it fascinating that Dr. Rivera is not motivated to commercialize his research. I find his passion for publicly sharing his sustainability and 3D printing advancements as a testament to the type of researcher he is: someone who prioritizes the greater good and the advancement of knowledge over personal gain or financial success. It is refreshing to see a researcher like Dr. Rivera who is driven by a genuine desire to contribute to the field and make a positive impact on society. His decision to prioritize public sharing of his research demonstrates a commitment to open collaboration and the dissemination of valuable information that can benefit not only the scientific community but also the general public. Dr. Rivera's approach serves as an inspiration for other researchers and highlights the importance of fostering a culture of knowledge-sharing and cooperation in the pursuit of sustainable and innovative solutions.

Third, Dr. Rivera shared with me his unpublished research where he is again using organic material to 3D print compostable and recyclable prints. Notably, in one project he is using gelatin to spin fibers into strings. Using these gelatin strings, he can weave or braid the threads into gelatin clothes. These clothes can then be sewn or pieced together to form different materials. Before seeing this project, I had never considered how the filament of 3D printing could be used as a textile. Additionally, in collaboration with Dr. Rivera's sustainability efforts, the gelatin is sourced from a variety of local establishments that would have thrown out the organic material. By using previously tossed gelatin in his work, Dr. Rivera is reducing the amount of organic material sent to landfills, reducing methane emissions from decomposing organic material, and therefore ultimately reducing greenhouse gas emissions. However, using organic materials in 3D printing is extremely difficult (as discussed with Kraynak, Blutinger, and now Rivera). Therefore, to maintain the structural integrity of the print, it is valuable to manipulate the viscosity of the filament. For Rivera, he cannot use pure gelatin to produce fibers. However, by mixing the gelatin with different concentrations of other organic filament materials (like beeswax), he can control the longevity of the fibers. Rivera hopes to share this research at the end of this academic year. Ultimately, Dr. Rivera's lab teaches two valuable lessons:

1. Enhancing sustainability efforts through 3D printing will be imperative for continued increased consumption. Future 3D printing research and development must continue in the field where researchers continue to be intentional about their sustainability efforts. In Rivera's lab, these sustainability efforts are traced back to sourcing alternative filaments like organic material and food waste. However, making the 3D printers more energy efficient will be essential for commercial use and scalability.
2. Challenging the status quo of how developers view 3D printing to incorporate sustainability interests. While 3D printing can help researchers develop prototypes for development and aid in advancements, the environmental impact 3D printers have cannot be overstated. To make the 3D printing community more sustainable, the community

must broaden its perspectives to include sustainability efforts with intentional design. 3D printing things “just to print” should be viewed as mindless.

As Dr. Rivera is funded by US’s NSF grants. It is optimistic that the United States is encouraging 3D printing innovation and sustainability through supporting labs like CU Boulder’s ATLAS Institute.

Part 3: Final Reflections

Conclusions

In conclusion, the work of American engineers Jack Kraynak, Dr. Jonathan Blutinger, and Dr. Michael Rivera showcases the diverse applications and potential of 3D printing technology as it pertains to organic materials and the future of mass-producing 3D printed foods. Kraynak’s research on minimizing cell death during extrusion bioprinting using a gelatin-alginate bioink has the potential to advance the field of bioprinting and accelerate the development of food applications. Blutinger’s innovative work on using digital lasers in 3D printing to create and prepare food challenges the status quo of the food industry and offers solutions for food safety, customization, and transparency. Rivera’s focus on sustainability in 3D printing, including the use of spent coffee grounds and organic materials, highlights the importance of considering the environmental impact of this technology and promoting intentional design for a more sustainable future. These researchers exemplify the spirit of innovation and disruption in their respective fields, pushing the boundaries of what is possible with 3D printing. It is crucial to support and respect their efforts as they strive to make a positive impact on society and advance the capabilities of this transformative technology.

Works Cited

Alexandra. "When Was 3D Printing Invented? The History of 3D Printing -." *BCN3D Technologies*, 15 May 2020, www.bcn3d.com/the-history-of-3d-printing-when-was-3d-printing-invented/. Accessed 12 Dec. 2023.

Fidan, Ismail, et al. "Recent Inventions in Additive Manufacturing: Holistic Review." *Inventions*, vol. 8, no. 4, 1 Aug. 2023, p. 103, www.mdpi.com/2411-5134/8/4/103, https://doi.org/10.3390/inventions8040103. Accessed 15 Aug. 2023.

Tripathi, Swikriti, et al. "3D Bioprinting and Its Innovative Approach for Biomedical Applications." *MedComm*, vol. 4, no. 1, 24 Dec. 2022, www.ncbi.nlm.nih.gov/pmc/articles/PMC9790048/, https://doi.org/10.1002/mco2.194. Accessed 12 Dec. 2023.

Gross, Doug. "Obama's Speech Highlights Rise of 3-D Printing." *CNN*, CNN, 13 Feb. 2013, www.cnn.com/2013/02/13/tech/innovation/obama-3d-printing/index.html. Accessed 12 Dec. 2023.

Health Care Products. "What Is Medical 3D Printing—and How Is It Regulated?" *Pewtrusts.org*, The Pew Charitable Trusts, 5 Oct. 2020, www.pewtrusts.org/en/research-and-analysis/issue-briefs/2020/10/what-is-medical-3d-printing-and-how-is-it-regulated. Accessed 12 Dec. 2023.

Team Xometry. "3D Printing in Medicine and Healthcare." *Xometry.com*, Xometry, 7 June 2023, www.xometry.com/resources/3d-printing/3d-printing-in-medicine-and-healthcare/. Accessed 12 Dec. 2023.

Zhu, Wenxi, et al. "Three-Dimensional Printing of Foods: A Critical Review of the Present State in Healthcare Applications, and Potential Risks and Benefits." *Foods*, vol. 12, no. 17, 1 Sept. 2023, pp. 3287–3287, www.ncbi.nlm.nih.gov/pmc/articles/PMC10487194/, https://doi.org/10.3390/foods12173287. Accessed 12 Dec. 2023.

Wakefield, Edward. "BluRhapsody 3D Printed Pasta by Barilla Now Available to Buy." *VoxelMatters - the Heart of Additive Manufacturing*, VoxelMatters - The heart of additive manufacturing, 6 June 2022, www.voxelmatters.com/3d-printed-pasta-created-by-barillas-blurhapsody-in-italy-of-course/. Accessed 12 Dec. 2023.

Jobs, Comeet. "Meat Products, Plant-Based, Compromise Free | Redefine Meat." *Redefine Meat*, Comeet Jobs, 31 Oct. 2023, www.redefinemeat.com/products/. Accessed 12 Dec. 2023.

Gonzalez, Melisa. "The Drinks of the Future 2D and 3D Printing Drinks - 3DPrint.com | the Voice of 3D Printing / Additive Manufacturing." *3DPrint.com | the Voice of 3D Printing / Additive Manufacturing*, 13 Mar. 2019, 3dprint.com/238190/the-drinks-of-the-future/. Accessed 12 Dec. 2023.

"MONA LISA 3D STUDIO." *Barry-Callebaut.com*, 2020, www.barry-callebaut.com/en-US/artisans/mona-lisa/3dstudio. Accessed 12 Dec. 2023.

Emminger, Ben. "3D-Printed Protein Bars Are Now a Thing You Can Buy." *Gear Patrol*, Gear Patrol, 24 June 2022, www.gearpatrol.com/fitness/a40407142/nourished-3d-printed-protein-bars/. Accessed 12 Dec. 2023.

"PancakeBot." *PancakeBot*, 2023, pancakebot.com/. Accessed 12 Dec. 2023.

"Scientists 3D-Print Seaweed Snacks for Kids." *Makewaterfamous.com*, 2022, www.makewaterfamous.com/news/seaweed-and-3d-printers-the-future-of-feeding-kids-d raft. Accessed 12 Dec. 2023.

Molitch-Hou, Michael. “Stealth Startup Captures Carbon by 3D Printing with Seaweed and Coffee Grounds.” *Forbes*, 31 July 2023, www.forbes.com/sites/michaelmolitch-hou/2023/07/27/stealth-startup-captures-carbon-by-3d-printing-with-seaweed-and-coffee-grounds/?sh=27aed5d777fd. Accessed 12 Dec. 2023.

Mendoza-Cerezo, Laura, et al. “Evolution of Bioprinting and Current Applications.” *International Journal of Bioprinting*, vol. 9, no. 4, 2 May 2023, www.ncbi.nlm.nih.gov/pmc/articles/PMC10261138/, https://doi.org/10.18063/ijb.742. Accessed 12 Dec. 2023.

“Utility Research Lab.” *The ATLAS Institute at University of Colorado Boulder*, 22 Aug. 2022, www.colorado.edu/atlas/utility-research-lab. Accessed 15 Dec. 2023.

“What Is 3D Printing?” Investopedia, Investopedia, 27 Nov. 2023, www.investopedia.com/terms/1/3d-printing.asp.

“MIT’s New Software Makes Multi-Material 3D Printing Easy.” TechCrunch, 11 Oct. 2016, techcrunch.com/2016/10/11/mits-new-software-makes-multi-material-3d-printing-easy/. Massivit 3D, www.massivit3d.com/.

“Japanese Additive Manufacturing: A Puzzle Box.” TCT Magazine, 27 Nov. 2023, www.tctmagazine.com/additive-manufacturing-3d-printing-industry-insights/japanese-additive-manufacturing-a-puzzle-box/.

“Charles Hull.” National Inventors Hall of Fame, www.invent.org/inductees/charles-hull.

“Our Story.” 3D Systems, www.3dsystems.com/our-story.

“3D Printing Has Months of Sundays History.” Medium, 27 Nov. 2023, medium.com/@2bdigital.dm/3d-printing-has-months-of-sundays-history-d7c036a48e2d.

"What Is Medical 3D Printing and How Is It Regulated?" Pew Trusts, 27 Oct. 2020, www.pewtrusts.org/en/research-and-analysis/issue-briefs/2020/10/what-is-medical-3d-printing-and-how-is-it-regulated.

"Is 3D Printing Eco-Friendly & Sustainable?" Perch Energy, 27 Nov. 2023, www.perchenergy.com/blog/innovation/is-3d-printing-eco-friendly-sustainable.

"3D Printing in Medicine: A Review of the Literature." 3D Printing in Medicine, vol. 8, no. 1, 2022, doi:10.1186/s41205-022-00134-y.

"FDA's Regulatory Framework for 3D Printing of Medical Devices Needs More Clarity." Pew Trusts, 27 Jul. 2022, www.pewtrusts.org/en/research-and-analysis/issue-briefs/2022/07/fdas-regulatory-framework-for-3d-printing-of-medical-devices-needs-more-clarity.

"3D Food Printing: A Trend to Watch." Advanced BioAdvisors, 27 Nov. 2023, www.adv-bio.com/3d-food-printing-a-trend-to-watch/.

"FDA Recommendations for 3D Printing Regarding Food Applications." Dynamism, 27 Nov. 2023, www.dynamism.com/learn/3d-printing/fda-recommendations-for-3d-printing-regarding-food-applications.html.

"Guide to Food-Safe 3D Printing." Formlabs, 27 Nov. 2023, formlabs.com/blog/guide-to-food-safe-3d-printing/.

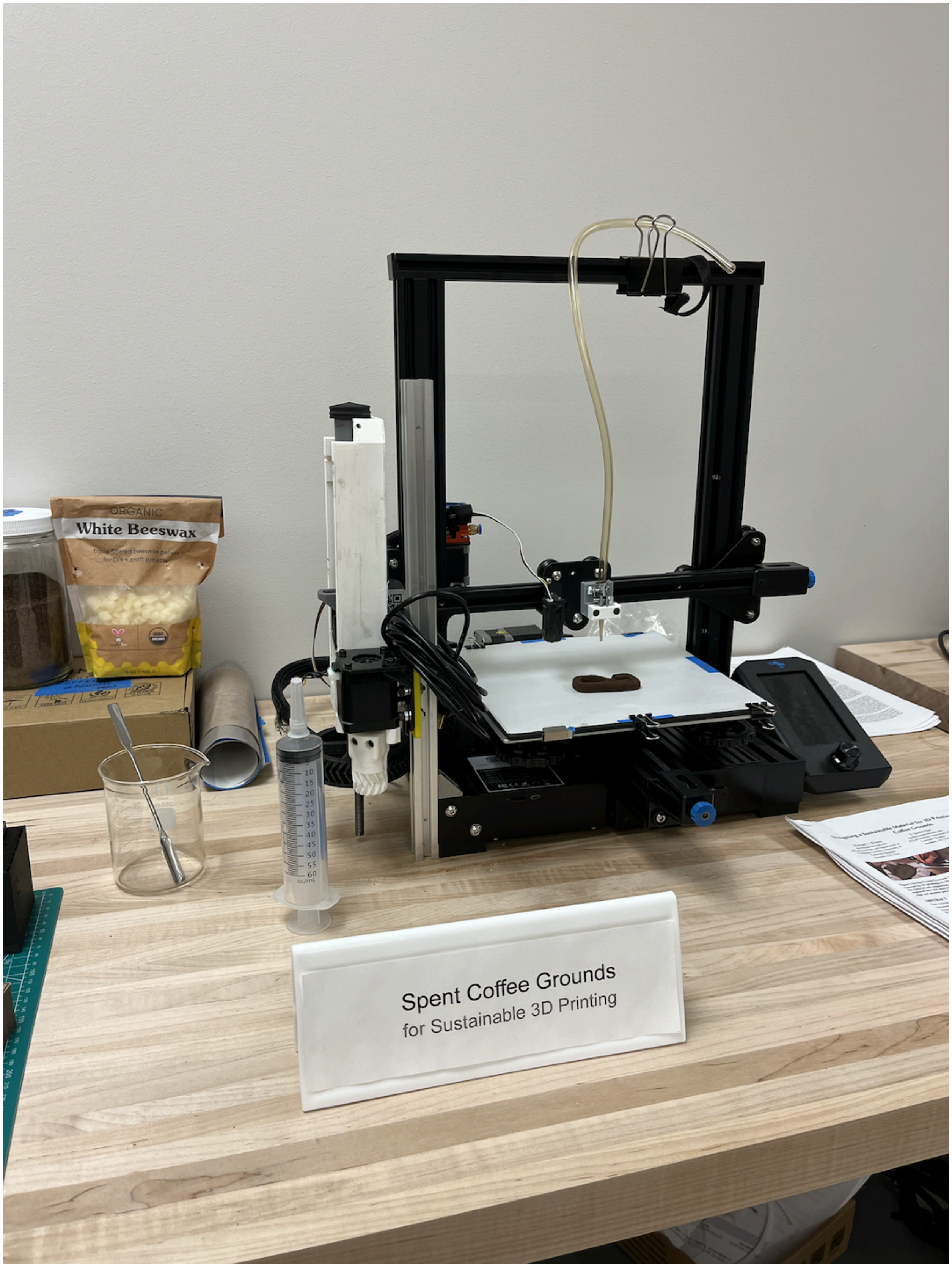
"3D Printing of Soft Materials: A Review." 3D Printing in Medicine, vol. 8, no. 1, 2023, doi:10.1038/s41538-023-00182-6.

Blutinger, Jonathan. "Jonathan Blutinger." Jonathan Blutinger, www.jonathanblutinger.com/.

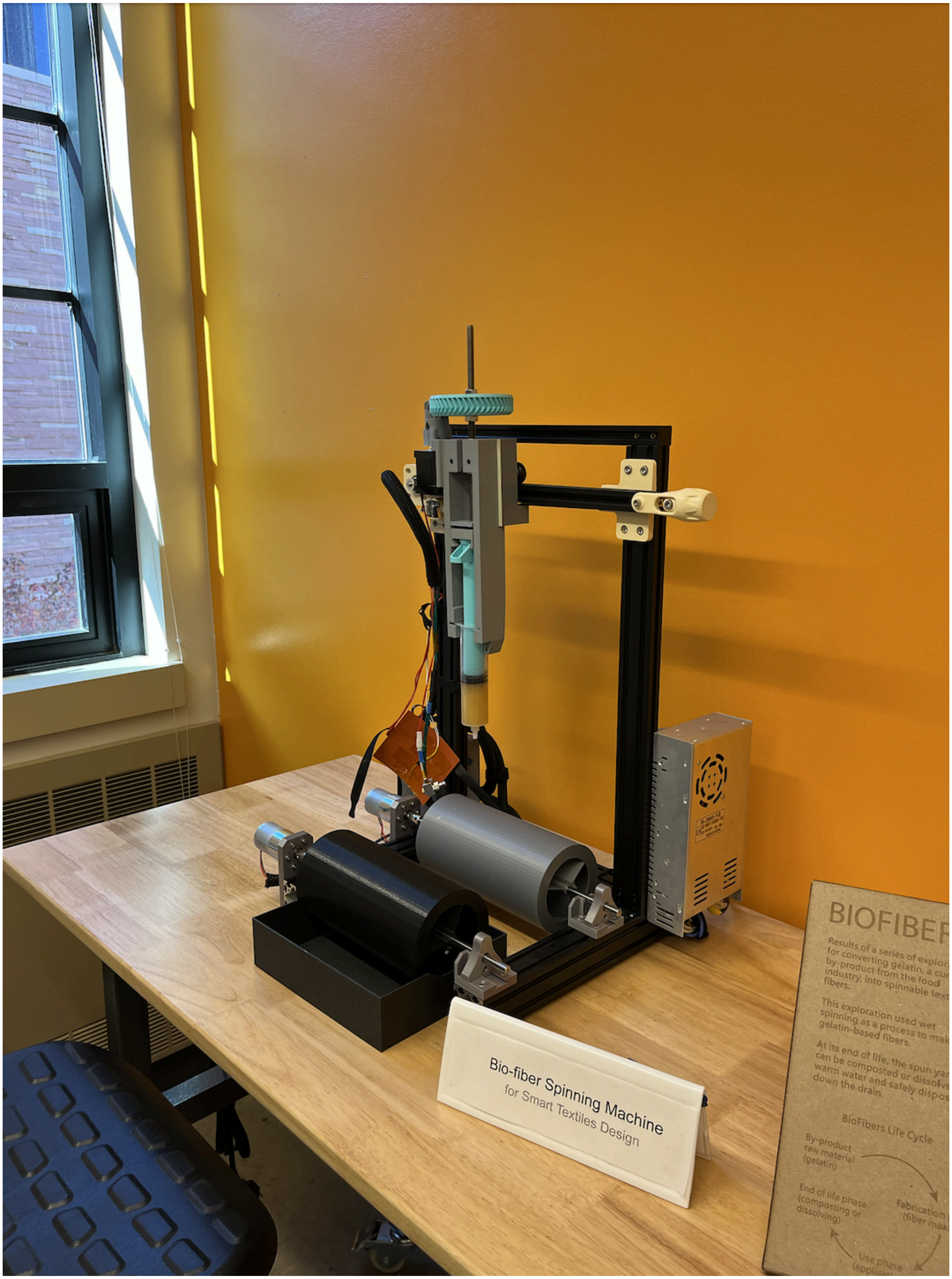
"Supplementary Video 1." Nature Communications, vol. 14, no. 1, 2023,

doi:10.1038/s41538-023-00182-6.

<u>Photos of Dr. Rivera's Lab</u>


ORGANIC
White Beeswax
Spent Coffee Grounds
for Sustainable 3D Printing


225-AN
ORGANIC
White Beeswax


Bio-fiber Spinning Machine
for Smart Textiles Design


BIOFIBERS
Researcher: Eldy S. Lazaro Vasquez
Collaborator: Institute for Textile Technology (ITA), RWTH Aachen, Germany
Advised: Laura Devendorf, Mirela Alistar, Michael Rivera (ATLAS Institute), Simon Kammler (ITA).
Results of a series of explorations for converting gelatin, a current by-product from the food industry, into spinnable textile fibers.
This exploration used wet spinning as a process to make gelatin-based fibers.
At its end of life, the spun yarn can be composted or dissolved in warm water and safely disposed down the drain.
BioFibers Life Cycle
By-product raw material (gelatin)
Fabrication phase (fiber making)
Use phase (application)
End of life phase (composting or dissolving)
Gelatin
Staple fibers
Multifilament
Spun yarn
RAW MATERIAL
FABRICATION PHASE