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3D Printable Hydroponics: A Digital Fabrication Pipeline for Soilless Plant Cultivation

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ABSTRACT Recently, 3D printing techniques have been devised to fabricate a range of functional systems, e.g., mechanical/electronic apparatuses, biological tissues, etc. Further building upon this trend, in this paper we describe a pipeline to digitally fabricate *hydroponic* systems, that support the cultivation of various plant species without the use of soil. The pipeline outputs a freeform 3D landscape with plant seeds attached onto its surface; by providing this printed foundation with adequate water and light (and later nutrient solutions), eventually the plants will grow, with the foundation effectively serving as a growth medium through which roots can permeate. The pipeline is flexible, and can be customized to suit different scales and applications. We demonstrate the effectiveness of our pipeline through quantitative evaluations, and also provide a list of plants that have been successfully cultivated using our technique. The paper will conclude with a discussion on how the pipeline may be further extended to realize fabrication of more complex ecological systems.

INDEX TERMS 3D printing, additive manufacturing, digital fabrication, hydroponics, ecosystem printing.

I. INTRODUCTION

3D printing (aka additive manufacturing), originally invented more than three decades ago, has now matured enough to see real-world uses in a variety of industries, including manufacturing, design, and medicine. Active research efforts continue to expand the range of printable materials, as well as the types of artifacts that can be fabricated using the technology. In addition to the technology's well known capacity to produce static objects with intricate geometries, new techniques have been developed that print out various *functional systems* with multiple interacting components, including mechanical systems (e.g., prosthetics [1], robots [2]), electronic systems (e.g., circuit boards [3]), chemical systems (e.g., batteries [4]), and biological systems (e.g., human organs [5]). The scale of 3D printable artifacts has broadened as well, as can be seen from advances in fields such as nanoprinting [6] and printable architecture [7, 8].

Further building on such trends, in this paper we introduce a digital fabrication pipeline for printing *hydroponic* systems that support the growth of various plant species. Hydroponics [9, 10, 11] refers to a method for growing plants without the use of soil, instead relying on industrially-produced substrate materials such as sponge, felt, polyurethane foam, rock wool, etc. The technology is used widely in commercial cultivation of a range of agricultural produce such as lettuce, tomato, and strawberry; it is also popularly used by individuals for indoor farming and gardening within their homes. In recent years, hydroponics is also seeing increased usage in city centers as a means to realize novel forms of urban horticulture, such as vertical garden walls [12].

Below are several of the main advantages of hydroponics over soil-based cultivation [11]:

- Can take a wider range of sizes and forms, making it more conducive to urban farming/gardening
- Requires less water, as water not absorbed by plants can be recirculated through the system
- Produces better yield given the same amount of space

Conversely, some of the main disadvantages of hydroponics include:

- Requires higher cost for initial setup
- Can be vulnerable to system failures, due to often relying on automated mechanisms for irrigation, lighting, etc.
- Requires supplemental application of nutrient solutions, since the inert substrate materials lack vital elements for plant growth such as nitrogen and potassium

While the capacity of some 3D printed materials to support plant growth has been demonstrated to limited extents within prior work [13, 14, 15], to our knowledge our work represents the first effort to describe a full pipeline that enables reliable plant cultivation supported by quantitative results. Potential benefits of printable hydroponics include facilitating the development of varied hydroponic systems tailored to different environmental conditions and/or plant types, integration with printable architecture enabling fabrication of diverse human habitats (e.g., house with garden), and the prospect of serving as a foundation on which further techniques to print *ecological systems* can be built.

A. RELATED WORK

While the origin of 3D printing can be traced back to the early 1980s, the technology has seen a surge of interest in the early 21st century, buoyed by movements in DIY communities [16, 17] such as the open-source RepRap project [18]. This recent rise of 3D printing has coincided with a broader rise of digital fabrication technologies in general (e.g., laser cutters, water jet cutters, CNC routers); collectively, such technologies have brought forth to manufacturing benefits such as reduction of prototyping speed/cost, greater creative freedom with regards to form, mass customization prospects, etc.

Development of novel 3D printing technologies is a flourishing field of technical research, pursued in diverse communities including material science, computer science, industrial/architectural design, and medicine to name a few. While there exist a number of active strands of 3D printing research, we view the following research directions as constituting the most relevant precedents to our work.

1) 3D Printing Functional Systems

Most 3D printers, including low-end models targeted towards hobbyists, are capable of fabricating functional systems with multiple interacting parts—for example, the online repository Thingiverse [19] hosts numerous variations of self-contained gearboxes that can be produced in a single pass using entry-level 3D printers. The expanding library of printable materials, and continued improvements in multi-material fabrication technology, have resulted in an acceleration of research into techniques for printing functional systems; some notable examples in this line of work include the following:

- Prosthetics [1, 20]
- Electronic circuits/devices, e.g., sensors [3, 21, 22]
- Robots, including soft robotics [2, 23]
- Batteries [4, 24]
- Biological tissues, organs, implants [5, 25, 26]

By realizing fully (or mostly) automated fabrication of complex artifacts that presently require skilled manual labor and/or specialized facilities to manufacture (or are practically impossible to manufacture otherwise), such technologies can be expected to bring down production costs and enable fine-grained customization for a range of artifacts, and also open new opportunities for DIY and OSH (open-source hardware) [27] movements. Our work on printed hydroponics, heavily inspired by such precedents, extends this line of work by introducing a pipeline to fabricate yet another class of complex systems—ecological systems—albeit their relatively simple manifestations involving only a subset of plant species.

2) 3D Printing Architecture

Some of the earliest works on 3D printing full-scale buildings were conducted in the early to mid 2000s [28, 29]. Since then, numerous approaches toward printable architecture have been investigated, both in and outside of academic research. The main proposed benefits of printable architecture include the reduction of waste material due to the nature of additive manufacturing, the prospect of rapid construction in resource-challenged (e.g., disaster-struck) areas, lower costs, and the potential to realize new architectural styles.

A sizable amount of academic research has been dedicated to developing new materials for printable architecture—a material conducive to rapid, large-scale printing, that simultaneously guarantees the necessary structural integrity for the printed buildings to withstand weight load, weather, etc. The majority of such efforts so far have concentrated on the use of fast-drying cementitious mixtures [30, 31, 32] that can be extruded using specialized large-scale 3D printers (frequently incorporating robotic arms), which give the printed buildings appearances similar to those of conventional concrete houses, albeit with visible seams between layers. Another approach is to strengthen thermoplastics such as PLA or ABS (polylactic acid and acrylonitrile butadiene styrene, respectively; two of the most commonly used materials in 3D printing) with fiber reinforcements [33]. Although numerous examples of 3D printed buildings have been publicly demonstrated, as of yet printable architecture has not been shown to be robust enough for widespread commercial application. For smaller-scale or temporary structures, however, unmodified PLA or ABS is often sufficient, and entire structures can be fabricated using commercially available, large-scale FDM (Fused Deposition Modeling) printers [34].

Such efforts on printable architecture have served as direct inspirations for our work; our original motivation for printed hydroponics came from the idea of broadening the scope of printable architecture by enabling fabrication of *semi-natural* elements that comprise our living environment (in addition to buildings per se)—e.g., lawns, gardens, rooftop farms, etc.

3) 3D Printing for Plant Cultivation

A modest number of prior efforts exist that utilize 3D printing for plant cultivation, constituting the most direct precedents to our work described in this paper. Most of these works have been carried out by corporations and DIY enthusiasts outside of academic research, focusing on the use of 3D printing to fabricate a subset of horticultural equipments (e.g., planters, drip nozzles) but not the growth medium (substrate) itself—relying instead on conventional growth media such as soil or clay pellets, which need to be procured separately. A number of online repositories [35] now exist that provide open-source 3D models of hydroponic hardware components.

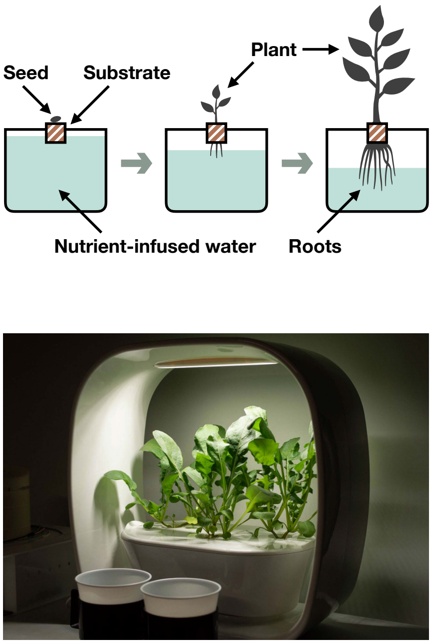

FIGURE 1. A simple technique for hydroponic plant cultivation, commonly referred to as the Kratky method (top). A commercially-available hydroponics kit based on the Kratky method (bottom).

There are a few examples in which 3D printed artifacts have been shown to effectively function as growth media for several types of plants [13, 14, 15]. However, quantitative data is lacking in all of these examples, and the demonstrated plant growth is relatively modest. As of yet, there have been no published work that describes 3D printing techniques that fabricate hydroponic substrates with evidence for reliable and sustained plant growth; nor have there been demonstrations of complete pipelines built around such techniques.

B. HYDROPONICS

Figure 1 depicts a simple setup for hydroponic plant cultivation, commonly called the Kratky method [36]. Initially, the lower end of the substrate is submerged in nutrient-infused water, which reaches plant seeds through capillary action and provides them with the moisture needed for germination. As plants grow, the water level will naturally go down; however, root growth will ensure that water continues to be absorbed, while the growing vacant space within the reservoir provides roots with access to oxygen.

A variety of materials can be used as the substrate, including clay pellets, coconut coir, peat moss, perlite, vermiculite, sponge, felt, rock wool, and polyurethane foam (the first five need to be held inside porous containers due to their granular nature). Below are several of the properties shared among the common substrates:

- Absorbs and holds water through capillary action
- Allows plant roots to grow through
- Provides structural support to plants
- Exerts negligible or modest effects on water pH levels

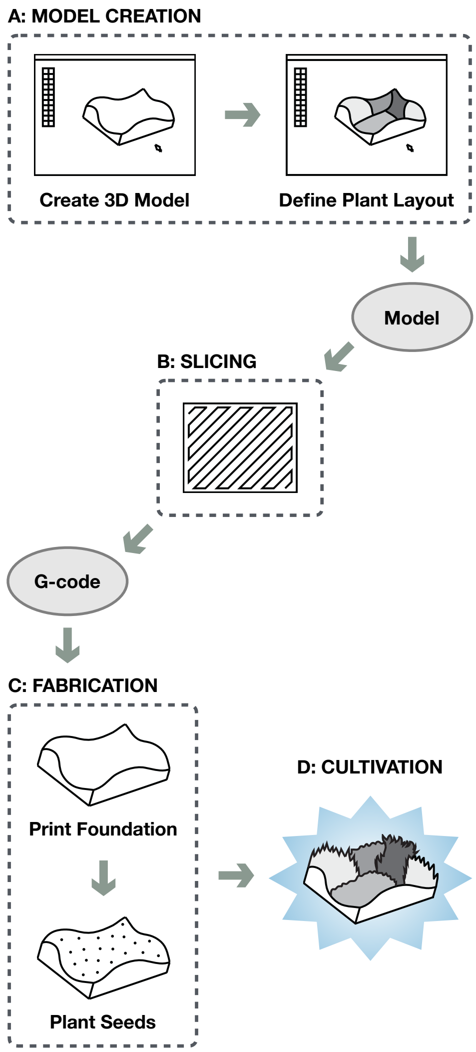

FIGURE 2. Printable hydroponics pipeline.

- Does not exude cytotoxic substances

The Kratky method is but one of the numerous varieties of hydroponic setups. Most configurations employ some kind of automated system (e.g., water circulation, controlled lighting, air pumps) to attain finer control of the growth environment, which brings benefits such as more predictable results, less water use, and lower space requirements. Irrigation can come in many forms as well; in addition to a reservoir-based setup like that depicted in Figure 1, methods such as drip irrigation, direct spraying of mist onto plant roots (*aeroponics* [37]), and nutrient film technique [38] (where plant roots are exposed to continuous flows of water) are often employed. The flexibility of configuration allows hydroponics to be used to cultivate a wide range of plant species, with highly different forms and physiological requirements.

Some notable variants of hydroponic systems include vertical garden walls where plants are grown on thin sheets of substrate (e.g., nylon felt) attached to building walls, vertical farms where hydroponic facilities are densely installed within high-rise buildings, and *aquaponics* where marine creatures such as tilapia are raised in pools alongside plants (excretions from the creatures provide nutrients to the plants) forming a symbiotic system [39].

In all cases, plants will need access to air, water, light, and nutrients for sustained growth.

II. PIPELINE

Figure 2 illustrates our digital fabrication pipeline for printable hydroponics. The initial stage of the pipeline is model creation, where 3D models of desired hydroponic systems are created by users, each consisting of a multi-material, three-dimensional geometry of the printed foundation along with the layout of plants to cover its surface. Completed models are then given as input to a slicing process, which converts them into *G-code* files, i.e., text data that can be read by the 3D printer to perform fabrication. Fabrication consists of two steps: printing the three-dimensional foundation (followed by post-processing), and placing plant seeds. The final stage of the pipeline is cultivation; providing adequate care in suitable environmental conditions will eventually trigger germination and subsequent growth of the plants.

A. MODEL CREATION

Model geometries are defined as standard mesh models, which can be created using 3D modeling applications such as SketchUp, Rhinoceros, etc. Plant layouts are defined using a custom software; geometries (saved as Wavefront .obj files) can be imported into this software, in which users specify plant-covered regions on their surfaces using a 2D painting interface (Figure 3). Each painted region is then converted into a set of seed-planting points, by overlaying a grid of dots (distance between the dots are varied based on plant species) onto the region from above.

Notice that the painting interface is in 2D, and our software does not allow users to paint (i.e., assign plants) onto vertical, or other acutely angled surfaces. This reflects a limitation of our seed-planting mechanism (described later), which drops seeds from above using syringe-based extrusion.

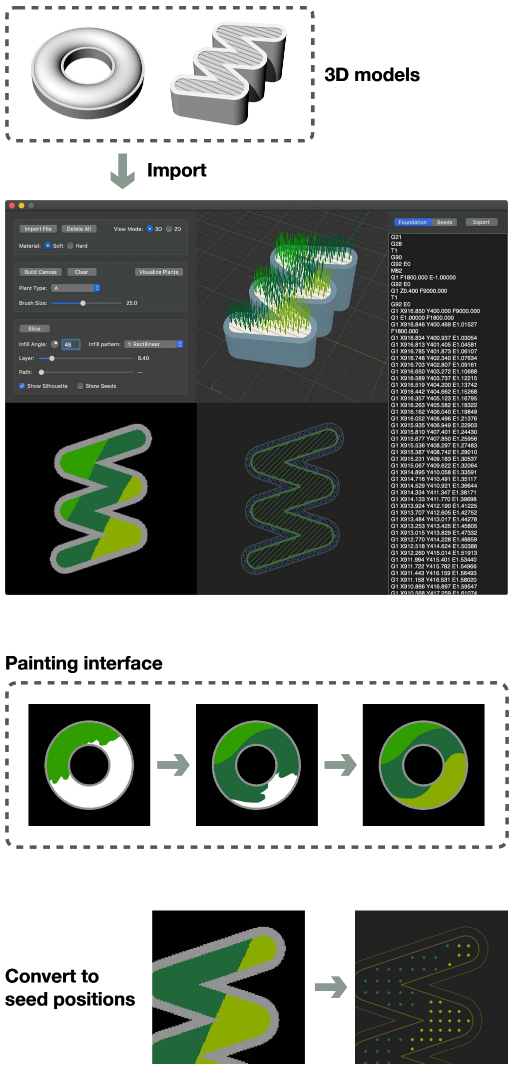

FIGURE 3. Model Creation. 3D models (in Wavefront .obj format) are imported into a custom software, in which users can define layouts of plants to be grown on their surfaces. User-defined plant layouts are automatically converted to seed positions.

B. SLICING

Slicing [40] refers to the procedure of converting 3D models into a set of low-level instructions (G-codes) that the printer hardware can interpret. For FDM printers, this usually entails first splitting the 3D model into a number of horizontal layers, and then planning the detailed hardware behavior (e.g., head movement, filament extrusion, etc.) needed to fabricate each layer. Naturally, even when printing the same 3D model, to obtain best results separate sets of G-codes must be generated for different printing materials and/or hardware.

In FDM printing, to conserve materials and decrease printing time, most layers are not printed as solid layers—instead, the internals of each layer are fabricated using a sparse infill pattern. In our pipeline we use a custom software for slicing, whose output prints out layers using a rectilinear grid pattern. However, in our case the sparse infill is employed not only as a means to conserve materials and printing time, but also to enable the printed volume to function as a hydroponic growth medium, allowing water, air, and plant roots to pass through (Figure 4). The slicing software can make local adjustments to grid densities, in both horizontal and vertical directions. Regions directly beneath plant seeds must be fabricated using denser patterns to provide ample physical support to plants, whereas regions deep inside the volume, or where no plants are expected to grow may contain more empty space. Density patterns should ideally be tailored for each printing task, as orientations of root growth can vary considerably depending on plant type, volume geometry, water availability, and other environmental conditions. Entirely solid regions can be fabricated as well, for purposes such as providing extra structural support, or realizing fine control of water flow within the printed volume. Foundations must not be covered with solid

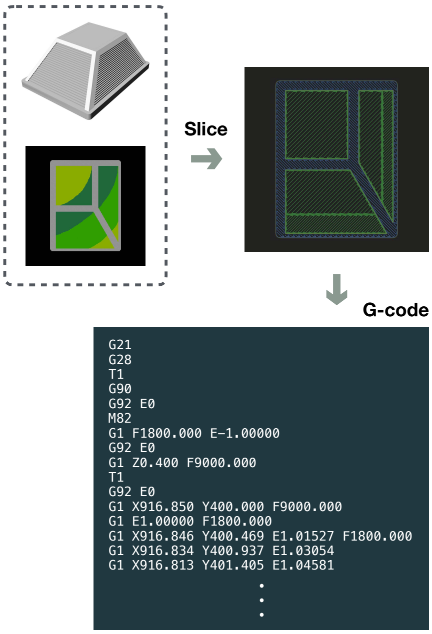

FIGURE 4. Slicing. The custom software generates two sets of G-codes, one for printing the foundation and the other for planting seeds.

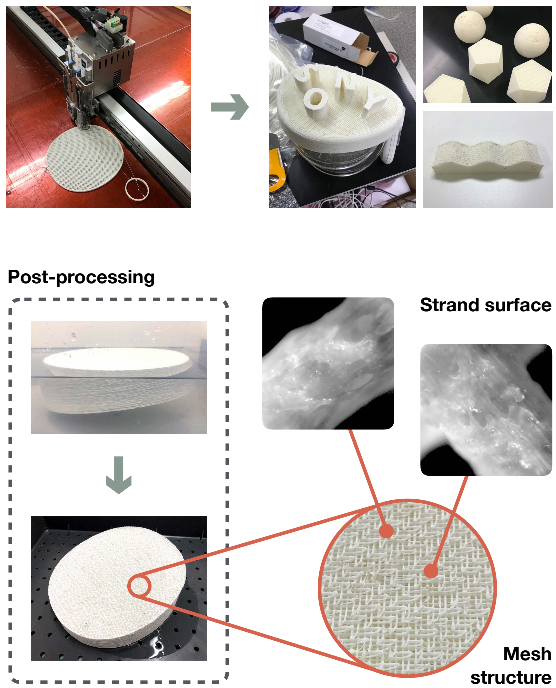

FIGURE 5. Fabricating the foundation. The foundation is printed using the SBS/PVA filament via a standard FDM process (top), and then soaked in water to dissolve the PVA components (bottom). Note how the printed strands exhibit rough surface textures with microscopic pores.

shells over areas on which plant seeds will be placed, i.e., the internal mesh structure needs to be exposed to the outside, in order to allow roots to grow inward.

C. FABRICATION

G-codes generated through slicing are read by the printer to perform the actual fabrication. In our pipeline, fabrication is split into two discrete steps: 1) printing the three-dimensional foundation, and 2) planting seeds onto its surface.

1) Printing the Foundation

To print the foundation, we use a filament material composed of a fine mixture of the following three substances (the weight ratio of SBS to PVA in the material is roughly 7 : 3):

- SBS (styrene-butadiene-styrene block copolymer)
- PVA (polyvinyl alcohol)
- Erucamide, added in small amounts as glidant

The hybrid filament can be printed using most FDM printers. As PVA is water-soluble, rinsing an object printed using this material in water results in microscopic pores opening up throughout its surface. The material was chosen based on the expectation that these pores will give the printed foundations water retention capabilities via capillary action, and also due to its plasticity which is a property of SBS (a synthetic rubber material used in shoe soles, tires, etc.) The filament can either be made in-house using dedicated equipment, or purchased as products (e.g., Porolay Lay-Felt, albeit with perhaps slightly different material compositions) marketed for their cloth-like texture to be used in 3D printed fashion, etc.

As described earlier, regions within the foundation directly underneath plant seeds are printed using fine rectilinear mesh patterns; other areas can be printed either sparsely or densely, to meet structural requirements, constraints on printing time and/or material use, etc. Once printed, the volumes are either soaked or rinsed in water to eliminate the PVA, which yields the desired material properties (Figure 5). The length of time needed for this post-processing will vary according to volume geometry and other conditions. Complete elimination of PVA is practically unattainable, but in our experiences we have not found remnant PVA to noticeably hinder plant growth.

Using multi-extruder 3D printers, foundations can be fabricated using a combination of the aforementioned material and other thermoplastics such as PLA or ABS. While regions printed using such materials will be unconducive to sustained plant growth, there are beneficial uses to multi-material printing such as improving the structural integrity of the volumes by embedding robust thermoplastic skeletons, constructing internal structures (e.g., pipes, pools) that facilitate irrigation and other maintenance tasks, and enhancing aesthetics.

2) Planting Seeds

In common hydroponic setups including the Kratky method, many types of plants can be grown by simply placing seeds on top of water-soaked substrates (e.g., rock wool)—the high water-retention capacity of the substrate material ensures that seeds will receive sufficient moisture to trigger germination. However, since the porous SBS volumes printed through our pipeline lack the same degree of water-retention capacity as common substrates, an alternative means to provide moisture

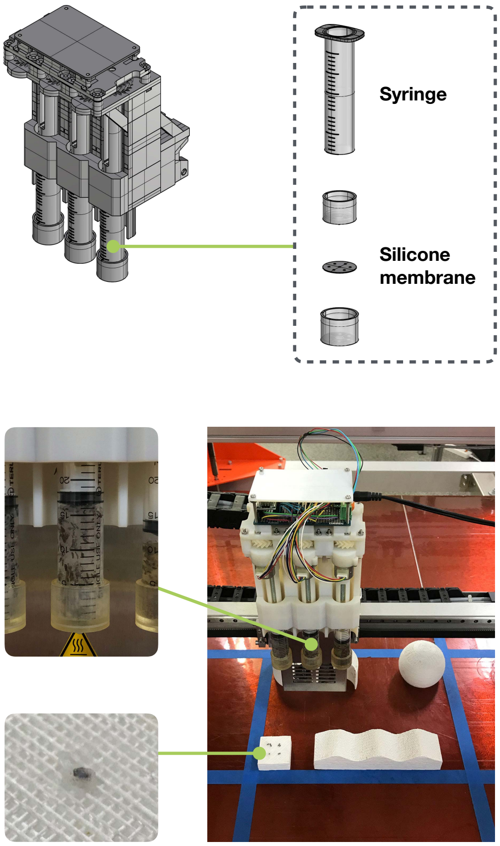

FIGURE 6. Planting seeds. The custom planting head is equipped with multiple paste extruders, which incorporate flexible silicone rubber membranes to prevent seeds from clogging the nozzles.

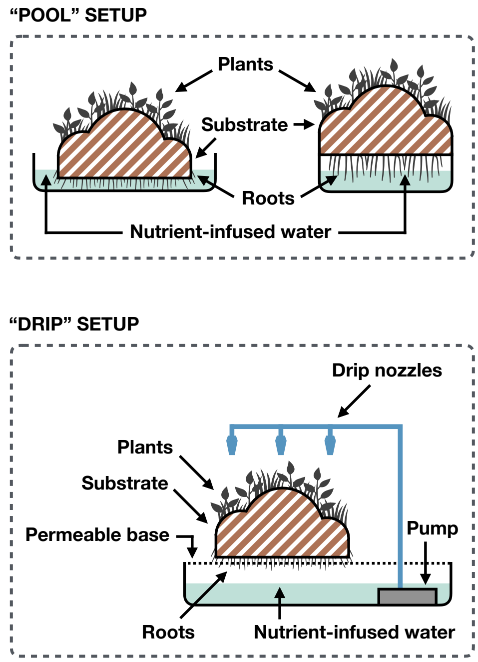

FIGURE 7. Examples of viable cultivation setups. In the “pool” setup (top), plant roots absorb water from a pool of nutrient-infused water, that may be refilled periodically or be voluminous enough to last for the entire duration of cultivation. In the “drip” setup (bottom), drip nozzles and a water pump is used to enable automated irrigation.

becomes necessary. (An exception to this is if the foundations are placed and routinely watered in climate-controlled rooms with high humidity.)

To this end, we coat plant seeds in superabsorbent polymer gel (sodium polyacrylate) [41, 42] before placing them atop the foundations. In addition to providing seeds with moisture, the gel also assists in affixing the seeds in place, preventing them from being washed away during irrigation, or dropping into mesh openings. Through experiments involving leaf lettuce seeds, we identified a polymer-to-water weight ratio of $3 : 1000$ to provide suitable balance between viscosity and germination rate. Increasing the amount of polymer relative to water will result in higher viscosity and better affixation of plant seeds; however, excessive viscosity can also lower rates of successful germination, by impeding roots from reaching the foundation’s surface.

We have designed a custom paste extruder to place the gel-coated seeds onto printed foundations (Figure 6). The design modifies a standard, syringe-based extruder [43] by replacing the plastic tip with a punctuated membrane of silicone rubber (Shore hardness $20A$, hole diameter $2mm$, thickness $0.5mm$ —again, determined through experiments using a limited set of plant seeds; optimal parameters will likely vary depending on seed geometry) to prevent the solid seeds from clumping together and clogging the nozzle tips. The extruder automatically moves to each of the seed-planting positions determined in the model creation phase, and extrudes a mixture of plant seeds and polymer gel. Multiple extruders can be installed on the printing head, which will allow different types of plant seeds to be placed on the foundation in a single pass.

There are several drawbacks to our automatic seed planting mechanism. The first is the inability to place seeds on vertical or acutely angled surfaces, due to the fact that the extruder is designed to drop seeds vertically from a distance. The second is the lack of precision; the extruder only has control over the volume of seed-gel mixture extruded at each location, and the exact number of seeds contained in that volume can fluctuate with each extrusion. The third is the additional limitations on the range of plantable seeds incurred due to the hardware; for example, the current head design (with its $2mm$ punctuation) often fails for seeds with large diameters or elongated shapes. Placing seeds by hand can alleviate such issues, albeit at the expense of automation benefits.

D. CULTIVATION

As plant seeds are vulnerable to dehydration during the early stages of their growth, printed foundations should be closely monitored (and provided with moisture as needed) until roots can be seen growing inward into the mesh structure. Ideally, the entire foundation should be enclosed within a plastic case etc. to minimize the escape of moisture. Other environmental conditions (e.g., lighting level) should be adjusted to suit the plants grown on the foundation.

FIGURE 8. 3D printed hydroponic systems, wholly fabricated using porous SBS (top); the systems were initially cultivated using an automated "drip" irrigation setup, but later moved to manual "pool" irrigation. 3D printed hydroponic systems made of a combination of porous SBS and PLA (bottom), cultivated manually using a "pool" setup.

Once seeds have sprouted successfully, subsequent maintenance can take a number of forms, just as with conventional hydroponics. In all cases, the plants need to be provided with water, light, air, and nutrients for sustainable growth. Figure 7 shows two examples of viable setups for printed hydroponics. The *pool* setup relies on periodic manual irrigation; here, the printed foundation either rests inside a water-holding pool, or multi-material printing is used to make the foundation's base itself hold water. In the *drip* setup, a water pump is used to continuously irrigate plants with nutrient-infused water. The rate of necessary irrigation will differ for each setup, but will generally need to be more frequent compared to conventional hydroponic setups due to the limited water-holding capacity of the porous SBS filament.

III. EXPERIMENTAL RESULTS

Figure 8 shows several examples of hydroponic systems that we have printed using the pipeline; Figure 9 and Table 1 show the types of plants that have been cultivated on the systems.

The effectiveness of the porous SBS mesh foundation for plant growth was evaluated by comparing with three common thermoplastic filaments (PLA, ABS, flexible TPU) printed in identical mesh structures, and also two hydroponic substrates (rock wool, sponge). For each of the materials, we prepared six cylinders with a diameter and height of both $4.0cm$, and grew leaf lettuce on their surfaces and observed the results.

All printing was performed using a BigRep ONE 2.0 FDM printer, equipped with two $0.5mm$-diameter nozzles and with modified electronics to support the addition of the custom seed-planting head. Cultivation was done inside a climate-controlled facility with temperature set to 22 degrees Celsius, and humidity kept below 50%. Test cylinders were continuously watered using automated drip irrigation. (Figure 10 shows our experimental setup within the cultivation facility.) All materials used in this test are readily available from DIY stores and online marketplaces.

We also conducted an additional test using six porous SBS mesh cylinders, this time fabricated in a slightly more sparse pattern. (We increased the interval between each mesh strand to approximately $2.00mm$ from $1.75mm$ in the original test; this value is likely the upper limit for our lettuce seeds, since intervals larger than this caused seeds to drop inside the mesh openings.) Again, we observed the growth of leaf lettuce on the six cylinders, under the same environmental conditions.

Table 2 shows the test results; here, the numbers indicate the fresh weight of each lettuce specimen, measured 38 days after planting. (These numbers do not include root weight, as measurement was performed after cutting off each specimen at the cylinder surface.) We can see that the average weight of lettuce grown on the porous SBS mesh was in line with those grown on rock wool and sponge, whereas other thermoplastic filaments yielded significantly poorer results. The sparse SBS mesh exhibited worse results as well, suggesting that for each plant type there may be an optimal range of mesh intervals conducive to its growth. No specimen grown on rock wool or sponge died before the 38 day mark, highlighting a capacity for reliable plant growth generally found to be lacking among the thermoplastic materials.

A closer look at the cylinders (after the lettuce specimens have been cut off) revealed how in the SBS cylinders, lettuce roots had grown to diameters approaching $1.0cm$; in contrast, roots failed to grow wider than the mesh intervals in the PLA, ABS, and flexible TPU cylinders. To see if this affects long-term plant growth, we printed extra sets of cylinders (three each, for porous SBS, PLA, ABS, and flexible TPU), and grew leaf lettuce for longer periods of time, again in the same environmental conditions. By the 46 day mark, all specimens

FIGURE 9. Plants cultivated using 3D printed hydroponics. The following plants appear in the above photos: basil, shiso, coriander, parsley, gypsophila, zinnia, astor, marigold, sunflower, lettuce, and tomato.

TABLE 1. List of plants cultivated using 3D printed hydroponics.

Arugula	Leaf lettuce	Mizuna	Basil
Shiso	Parsley	Zinnia	Aster
Marigold	Gypsophila	Sunflower	Tomato
Torenia	Coriander	Watercress	Mint

grown on PLA, ABS, and flexible TPU in this test had either died, or snapped at the base becoming unable to sustain their own increasing weights (Figure 11).

We also conducted a series of informal tests to observe the degree to which the SBS mesh foundations absorb and hold water via capillary action. Figure 12 shows SBS mesh cubes

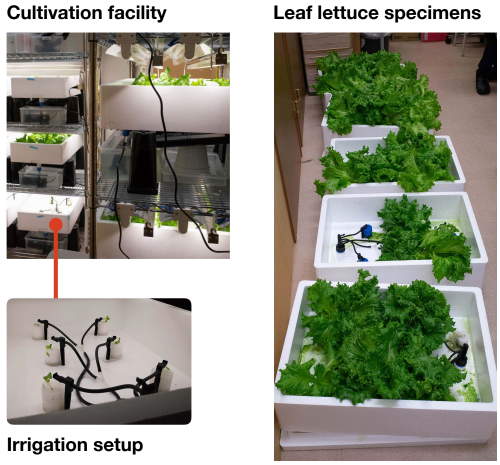

FIGURE 10. Interiors of cultivation facility used in our experiments (top left), irrigation setup (bottom left), cultivated specimens before measurement (right).

TABLE 2. Experimental growth results. Numbers denote fresh weights of lettuce specimens, measured 38 days after planting seeds. (0.0) denotes that the specimen had died before the 38 day mark. μ and σ denote mean and standard deviation, respectively.

Substrate	Sample fresh weight (g)						μ	σ
Sponge	94.7	120.1	48.7	103.3	57.2	93.0	86.2	25.2
Rock wool	70.1	83.6	128.6	126.6	117.0	84.0	101.7	23.2
Porous SBS	114.0	96.0	84.0	160.3	82.7	(0.0)	89.5	47.9
PLA (eSun PLA)	50.2	65.9	53.0	(0.0)	(0.0)	(0.0)	28.2	28.6
ABS (Verbatim ABS)	67.2	2.7	80.6	90.0	13.2	30.7	47.4	33.6
Flexible TPU (NinjaFlex)	70.9	64.8	11.6	51.2	(0.0)	(0.0)	33.1	30.0
Porous SBS, w/ sparse infill	131.5	113.0	20.4	86.6	(0.0)	(0.0)	58.6	53.8

($5 \times 5 \times 5cm$) after being placed for 30 minutes in a shallow pool of blue-colored water. We can see that the ability of the cubes to absorb and draw up water—although visibly present—is relatively modest, and not at a level comparable to those of materials such as sponge or rock wool. Figure 13 compares the relative water retention abilities of three materials (porous SBS, PLA, and sponge), by plotting changes in their weights after soaking $3 \times 3cm$ cubes of each material in water for 10 minutes. We can see that the porous SBS mesh is significantly more effective at retaining water compared to the PLA mesh (the difference becomes increasingly pronounced over time), but its water-holding capacity is still rather limited compared to that of sponge.

IV. DISCUSSION

Overall, our experimental results show that the porous SBS material yields sustainable plant growth that is unattainable with other common thermoplastic filaments. The most visible difference from other thermoplastics was how the SBS mesh

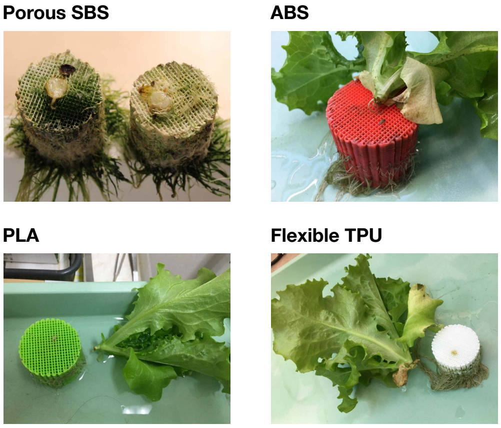

FIGURE 11. Porous SBS mesh cylinder, after lettuce specimen was cut off for measurement at the 38 day mark (top left). ABS, PLA, and flexible TPU mesh cylinders, after lettuce specimens had spontaneously broken off between the 41 and 46 day marks (top right, bottom left, bottom right). Note the differences in root diameters.

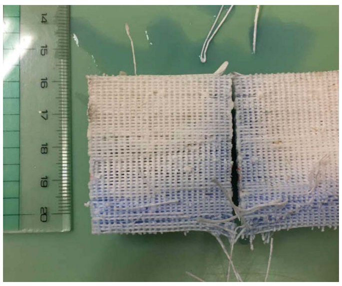

FIGURE 12. Porous SBS mesh cubes, after being placed for 30 minutes in a shallow pool of blue-colored water. Note how water has ascended to higher levels at the corners compared to the center.

strands progressively warped and fractured to accommodate root growth; the same was not observed with other thermoplastics, even with flexible TPU which feels noticeably softer to touch compared to ABS or PLA.

However, the results also show the water-holding capacity of porous SBS to be relatively modest, compared to those of common hydroponic substrates (e.g., sponge). Our results are inconclusive with regards to precisely how much this modest water-holding capacity is contributing to plant growth. The fact that other thermoplastic filaments—with minimal water-holding ability—managed to support lettuce growth to some extent (albeit with steady automated irrigation) suggests that strand flexibility and brittleness play more pivotal roles than water-holding ability in realizing sustained plant growth. We suspect that water-holding ability serves as a buffer of sorts, that makes the hydroponic system more robust to temporal fluctuations in temperature, humidity, water availability, etc., and is a *desirable* (as opposed to vital) property for achieving reliable plant growth.

If we can pinpoint the exact set of properties (mechanical, chemical, etc.) a material must possess to effectively function as a printable hydroponics substrate, it will open the doors to targeted developments of new filaments with advantages such

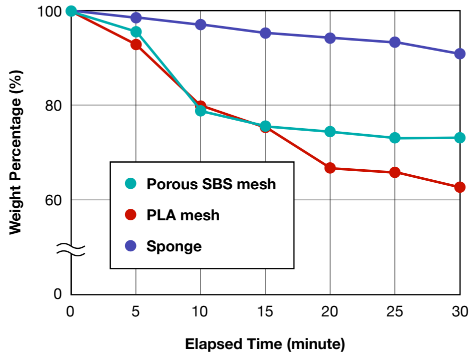

FIGURE 13. Relative weight decreases due to water drainage of porous SBS, PLA, and sponge cubes, after being soaked in water for 10 minutes. Average values of three trials.

as biodegradability, increased strength (e.g., torsional, shear), lack of need for post-processing, lower cost, non-toxicity, etc. New materials that alleviate the life-cycle environmental burden of printable hydroponics would be particularly desirable, especially as hydroponic systems are often deployed at large scales, e.g., vertical garden walls. (Sources of environmental concerns regarding printed hydroponics include not only the material used to print foundations, but also the liquid nutrient solution—typically derived from petroleum—and the super-absorbent polymer used in seed planting [44]. We have tried using other, more environmentally-friendly absorbents such as the seaweed-derived sodium alginate [45], but so far failed to obtain usable results.)

In our limited experiments, we found that as a general rule, plants that can be grown on conventional hydroponic setups can also be cultivated without issues on printed hydroponics. Due to differences in material properties, however, we expect further investigations to uncover a range of plant species that show disparate growth between conventional and printed hydroponic setups; particularly, we expect printed hydroponics to have difficulties growing plants that demand stringent environmental conditions to be met at the germination stage. (Conversely, the higher geometric freedom of printed hydroponics may prove advantageous for some plants.) As shown in Figure 14, printed hydroponics can sometimes attract algae and mold, just as with conventional hydroponics. While such unintended growth may typically be regarded as a nuisance, it also hints at the possibility of using printed hydroponics to cultivate lichens, mushrooms, etc.

FIGURE 14. Growth of white mold (left), growth of algae (right).

V. APPLICATIONS AND FUTURE WORK

As with 3D printing technology in general, printable hydroponics has a natural aptitude for mass customization; creating a complex-shaped, one-shot foundation takes no more time or cost compared to printing geometrically plain foundations of equivalent volume. Conventional hydroponic setups can take a variety of forms, tailored to environmental conditions, plant species, availability of space/water/electricity, etc.; a versatile 3D printing technology for hydroponics may provide benefit by minimizing the effort and cost needed for such customizations. Although not explored in much detail at the moment, by using multi-material printing and other advanced digital fabrication techniques, it should be possible to fabricate hydroponic systems fully integrated with automated irrigation/ maintenance equipments (e.g., pipes, drip nozzles, reservoirs, etc.)—realizing a *turnkey* experience where 3D printers print out finely tailored hydroponic solutions as complete products that can be immediately installed and activated by users with minimal additional effort. Overall, we expect the technology to have the effect of lowering the hurdles toward hydroponic horticulture/agriculture, leading to increased adoption and wider varieties in their forms and usages.

The aptitude for mass customization may be useful in some rather esoteric applications as well, as listed below:

- Niche agricultural uses, such as growing fruits into specific shapes by integrating 3D printed molds
- Use in agricultural and horticultural research, as a means to easily generate varied environmental conditions for studying plant growth
- Artistic uses, such as creating sculptures, furniture, installations, etc. that incorporate live plants

Our pipeline relies on FDM 3D printing, which is an easily scalable technology [34]. Though issues such as material cost and printing speed currently limit the practicality of large-scale 3D printing, technically it should be straightforward to expand printable hydroponics to architectural scales, realizing printable gardens, farms, etc. This may be combined with existing printable architecture techniques to open up some intriguing new possibilities—for example, (taking cues from traditional Icelandic *turf houses*) we can imagine fabricating temporary refugee shelters whose surfaces are covered with turf, that offer superior thermal insulation in cold climates.

Another interesting prospect of printable hydroponics is to use the technology as a foundation for printing more complex *ecosystems* that not only support the growth of plants but also provide suitable habitats for fish, birds, insects, etc. Creation of vivariums and terrariums is a longstanding field with a rich accumulation of knowledge (for example, a number of well-established techniques exist regarding the design of miniature sanctuaries for endangered fireflies), which should serve as a guide to future research in this direction. Through a marriage of such existing know-how and printable hydroponics, we may someday see a future where the local flora and fauna of a region can be computationally planned and sculpted by strategically introducing patches of 3D printed ecosystems; a future where networks of printed ponds, marshes, etc. restore lost biodiversity in dense urban centers.

Our near-term plans for future work include searching for alternative (preferably biodegradable) filament materials that reduce the overall environmental cost of printable hydroponics, refining the seed-planting mechanism to boost reliability and enable planting even on acutely angled surfaces, and further experimentations under more varied conditions to obtain better understandings of both the advantages and limitations of the technology.

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