Printable Hydroponic Gardens: Initial Explorations and Considerations

Yuichiro Takeuchi
Sony Computer Science Laboratories Inc.
3-14-13 Higashigotanda
Shinagawa-ku, Tokyo 141-0022 Japan
yutak@acm.org

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Abstract

Digital fabrication, in particular additive manufacturing technology (aka 3D printing), has now emerged as a popular topic of investigation in both academic and DIY/makers circles. Of particular attention lately are techniques for fabricating *functional systems* as opposed to static objects—e.g., electronic/mechanical apparatuses, biological tissues, etc. Building upon this trend, in this paper we explore the concept of *printable hydroponic gardens*, lushly adorned with various types of actual, living plants. The paper will describe our initial investigations into the topic, which have mostly focused on searching for 3D printable materials that can serve as effective substrates for plant growth. We will also discuss the potential utility of printable gardens particularly for dense, urban centers, and how the concept may be viewed as an initial step towards fabrication of more complex, holistic natural environments—i.e., *printable nature.*

Author Keywords

Printable garden; digital fabrication; 3D printing; hydroponics; printable nature; habitable media.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

Introduction

Within the past several years, 3D printing has quickly established its current status as one of the most hotly debated technologies of the moment. Though the amount of surrounding hype may tempt one to dismiss it as a mere short-term fad, the technology is already used to practical benefits in an array of industries, including manufacturing, design, and medicine. The technology has attracted interest in the HCI community as well, and a variety of techniques for fabricating *functional, interactive systems* have been proposed, such as optics [20], speakers [12], etc. Outside of the HCI community, many of the cutting-edge academic research on 3D printing also explore the fabrication of *functional systems*, for example batteries [17] and human organs [15]. A major advantage of 3D printing lies in the ease with which it can handle geometric complexity; recent efforts are progressively extending that capacity to functional complexity as well.

Following this trend, we have also been exploring the fabrication of functional systems. However, instead of targeting electronic/mechanical apparatuses or biological tissues, we are aiming to fabricate *ecological systems*—namely *hydroponic gardens*. Hydroponics refers to the cultivation of plants without the use of soil, instead relying on industrially-produced substrates such as sponge or felt. Our investigations so far have primarily concentrated on identifying 3D printable materials that can serve as effective hydroponic substrates; the goal is to realize techniques to fabricate 3D objects that—if given light and water—eventually turn into lush gardens covered with plants. We have devised two techniques that yield reasonably promising results, both implemented by hacking a common FFF (Fused Filament Fabrication) 3D printer.

The paper will first provide an overview of the concept of 3D printable gardens, and describe its potential benefits in facilitating gardening, particularly in dense urban centers. Next, we introduce our two implemented techniques, which both output small-scale gardens while relying on different sets of materials as substrates. We will discuss the pros/cons of each technique, and illustrate the different usage scenarios for which they each may be suited. Finally, the paper will conclude by discussing the future possibilities of the concept, how it can potentially be extended to open up a new direction for digital fabrication research.

Why Printable Gardens?

The main (although still hypothetical) advantages of 3D printing gardens over relying on existing techniques can be summed up in two words: 1) convenience, and 2) flexibility.

The use of 3D printing can potentially take away much of the need for manual labor and specialized know-how from garden making, significantly reducing the hurdles that novices encounter when taking up gardening for the first time. Also, the distinctively high degree of geometric freedom makes it possible to print gardens that fit exactly into any nook or cranny in a building; an unused corner can be turned into a small basil farm, and vacant spaces on walls can be turned into vertical gardens. Cost is still an issue with 3D printing, but as we learned from our initial explorations plants can be grown on relatively cheap materials, and both the initial investment and running costs of 3D printers are quickly decreasing in accordance with their wider adoption.

The above advantages make printable gardens a particularly attractive option for dense urban centers such as Manhattan or central Tokyo, places where the severe lack of open space calls for innovative approaches to increase greenery.

Related Work

Additive manufacturing technology (aka 3D printing) was originally invented more than three decades ago, and while its use in manufacturing processes has been steadily growing, the technology was not the target of much public attention throughout most of its history. The current hype was largely triggered by activities in the DIY/maker communities—most representatively by the Fab@Home [3] and RepRap [5] projects, both originating in the mid 2000s. Within the academic HCI community, though the usage of 3D printing / digital fabrication technology has been growing for some time as a tool to assist hardware prototyping, it is only within the past 4 to 5 years that the development of new digital fabrication techniques itself has become a mainstream research topic. Reflecting the field's core interests, HCI research in this vein has focused on devising techniques to fabricate *interactive* objects, such as optics [20], speakers [12], electronic circuits [13], and touchscreens [16]. HCI has also made sizable contributions to the development of 3D design tools [8], which can play important roles in making 3D printing / digital fabrication more accessible to experts and non-experts alike.

Our work on printable gardens may be considered proximate to the emerging field of *printable architecture*. Although one-shot fabrication of entire functional buildings [14] still appears to be in the conceptual stage, 3D printing building components for later, on-site assembly has become a (reasonably) feasible approach with real-world projects being carried out throughout the world [2]. At smaller scales, the use of 3D printing to create tailored building elements such as hinges and joints are already in wide use in high-end architectural projects. Looking outside of 3D printing, other, more esoteric approaches for automated building construction are being explored as well, such as the use of coordinated drones as robotic bricklayers [9].

Several direct precedents do exist for our work on printable gardens. Print Green [4] is an art project that uses a paste extruder to fabricate freeform 3D gardens using a mixture of soil, water, and plant seeds. In time the seeds germinate inside the printed structure, and plants begin to emerge from its surface. 3Dponics [1] is a project that provides open-source, downloadable files for hydroponics equipment such as planters, sprinkler nozzles, etc. The focus is not on printing entire gardens (users need to manually assemble the printed parts, fill planters with externally-sourced substrates, plant seeds, etc.) or to propose novel 3D printing techniques, but to build an open-source platform that assists novice gardeners with access to commodity 3D printers (e.g., MakerBot). Devising gardening support tools is a popular activity in the DIY/maker/design communities, and proposed ideas are not limited to high-tech solutions; for example, using cardboard structures to assist outdoor gardening is a popular technique [6].

Our work is distinct from such precedents in that we aim to print *entire gardens*, and also that our gardens are *hydroponic*. This leads to several advantages. Printing entire gardens (as opposed to printing parts that are later assembled by hand, like 3Dponics) results in further minimization of manual labor, and also gives greater freedom with regards to the gardens' forms. Printing hydroponic gardens (as opposed to using soil,

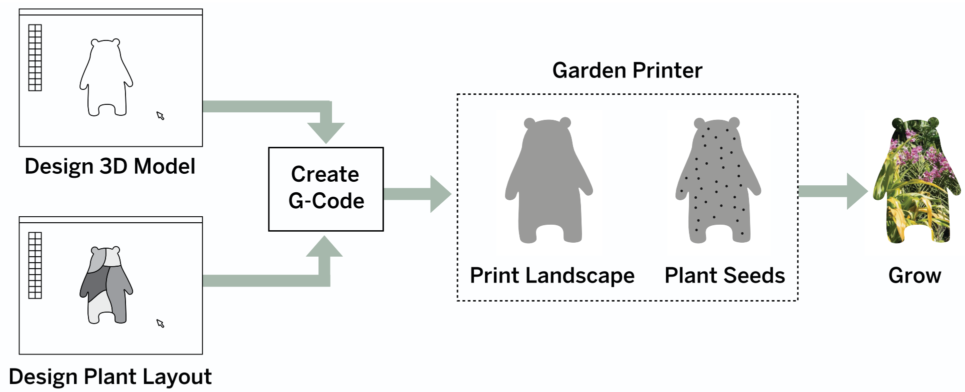

Figure 1: Idealized printable garden workflow.

like Print Green) can result in longer-lasting gardens resistant to erosion that can theoretically be maintained for many years (and harvested repeatedly if growing edible plants), and yield more predictable results as industrial substrates tend to be more consistent in quality compared to natural soil. We believe such strengths make our approach more attractive for novice urban gardeners with limited access to open space. Furthermore, as will be explained later, our approach can potentially be extended to realize fabrication of not only simple gardens but more complex, holistic natural environments (*printable nature*).

Garden Printing Workflow

Figure 1 illustrates our conceptualization of an example garden printing workflow. Using a custom 3D modeling software, users first design a freeform, 3D landscape on their computers (e.g., PC, tablet, smartphone). Next, using a "painting" interface, users determine the layouts of plants on their gardens by painting the 3D landscape using different colors, each corresponding to a specific type of plant. The user-defined layout is analyzed and converted into seed positions; the 3D printer will later plant seeds in these exact locations.

The 3D landscape and seed positions are then given as inputs to a custom slicing software, and translated into G-Code—a language widely used to control the actual movements of 3D printers (and other numerically-controlled tools such as plotters, lathes, and CNC mills). The printer interprets the G-Code, and fabricates the 3D landscape while also embedding plant seeds.

The printer's output will be a somewhat bland-looking 3D landscape, which at first will be devoid of any signs of vegetation. Hydroponic gardens, like all gardens, require light and water in order to grow. The garden will need to be either put in a place that receives direct sunlight throughout daytime or under artificial light, and will need to be periodically given water mixed with nutrient solutions (this is necessary since hydroponic substrates are devoid of nutrients, unlike natural soil). Eventually, the seeds will germinate and plants will begin to appear—growth speed will vary depending on landscape (substrate) material, plant type, and various environmental conditions.

The workflow in Figure 1 is an idealized one, and in our initial explorations (which will be described in the following sections) we employ a slightly more complex workflow, in order to make use of existing software as much as possible. First, instead of building a custom 3D modeling application we used Rhino 5, and built an additional painting software to determine plant layouts that takes OBJ files (exported by Rhino) as input. Next, instead of building our own slicing application we used

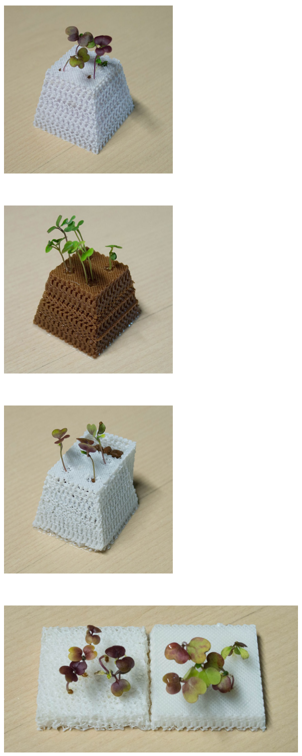

Figure 2: Initial experiments involving plastic mesh structures.

Slic3r, and built an interpreter software that takes its raw output and adds a series of custom G-Codes.

Initial Explorations

As we have mentioned earlier, most of our efforts so far have concentrated on finding a suitable substrate material—a material that is easily printable, and is also highly conducive to plant growth.

Initially, inspired by the fact that sponge and urethane foam are two of the most widely used substrates in hydroponic gardening, we tried printing fine mesh structures using a range of common 3D printing materials (e.g., PLA, ABS), and planting herb seeds by hand on top of those structures (Figure 2). While this has led to successful germination, the plants needed near-constant watering to survive which makes the technique impractical for real-world gardening; as we used a common FFF printer (MendelMax 2.0) to fabricate the meshes, the finest structure we could print was still too coarse to hold water as effectively as sponge or foam. Specialized 3D printers that can fabricate finer microstructures do exist and we plan to explore their use as future work, but the slow printing speed makes this a nonviable approach, at least in the immediate future.

Through a series of experimentations, we have found two approaches that reasonably fulfill the two criteria of easy printing and successful growth, which we describe in the following sections. Note that by no means we claim that these are the only viable approaches towards printable hydroponic gardens—our explorations have been more haphazard than systematic in nature, and we believe there to be a whole class of suitable materials. We hope that by sharing this information, we can help trigger similar, more principled explorations that will lead to discoveries of superior techniques.

Naturally, our explorations have produced a number of failed attempts as well. Some unsuccessful material choices include silicone rubber, wood pulp, coconut fiber, and a combination of PLA mesh and extruded polyurethane foam (similar to [11]). This paper will not provide further details about these attempts.

Yarn-Based Garden Printing

The first technique uses yarn as the substrate material. Technology-wise, this is only a simple extension of Hudson's technique for fabricating felt-like objects [10]. As felt is a popular hydroponic substrate used in many real-world applications such as vertical gardens [7], we hypothesized that a landscape made out of printed felt would also perform well as a hydroponic substrate.

Figure 3 shows our yarn-based garden printer, a hacked MendelMax 2.0. The only modifications we have made are the addition of custom printing heads, one for fabricating the felt-like landscape, and the other for embedding (or more accurately, dropping) plant seeds.

The felt printing head is a straightforward replication of Hudson's technique, with some minor adjustments to compensate for subtle differences in yarn quality, felting needle dimensions, etc. The head functions by continually feeding yarn from a spool, and repeatedly punching it with a felting needle to entangle it with the layer below. Printed out layer by layer, slowly the entangled yarn will build itself into the form of the 3D model. The seed planting head has been designed from scratch for this technique. The head contains a large internal disk, which in turn stores various types of plant

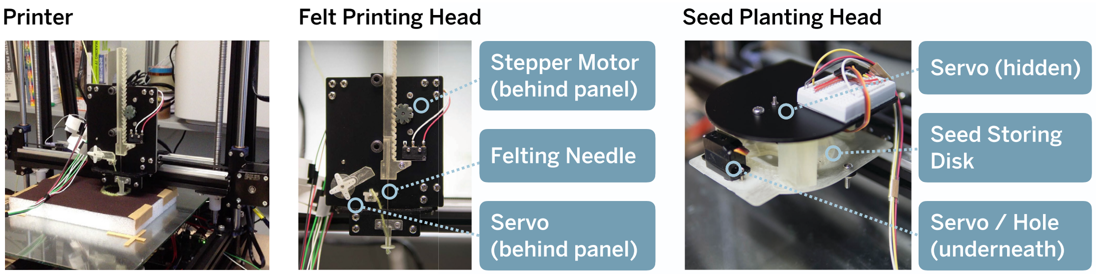

Figure 3: Yarn-based garden printer.

seeds along its perimeter. The head uses a combination of two servo motors to let designated seeds drop and freefall onto the felt substrate. Due to this simple mechanism, the head is incapable of accurately planting seeds onto acutely angled surfaces. Moderate slopes usually do not pose problems, as seeds get caught by the substrate's rough surface texture.

Note that since the MendelMax lacks the room to install two printing heads next to each other, we needed to manually switch printing heads during the fabrication process. Specifically, we first print the landscape using the felt printing head, and then switch to the seed planting head to drop seeds from above. This manual switching can be omitted if we use larger printers with enough space to install multiple heads simultaneously. Generally speaking, throughout our initial explorations our implementations have been quite bare-bones—a polished user experience is something we set aside for future work.

Figure 4 shows several examples of gardens printed using this technique. As mentioned earlier, hydroponic gardens require light, water and nutrients to grow into

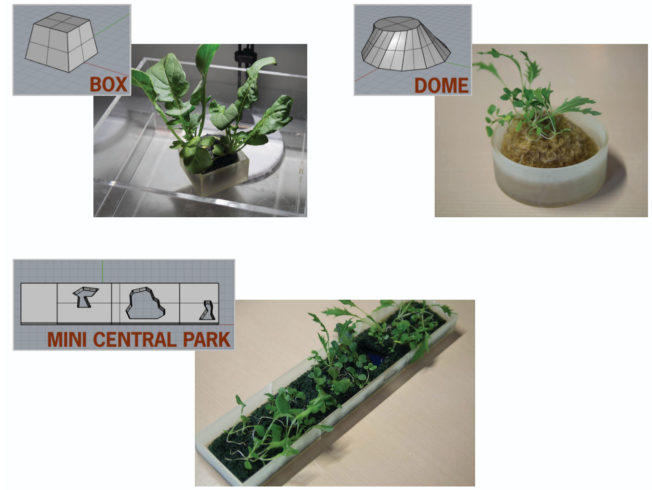

Figure 4: Yarn-based gardens.

a full-fledged garden. Since the printer only outputs chunks of yarn embedded with seeds (we used various common herbs typically grown in small-scale indoor gardening, such as arugula, basil, watercress, lettuce, and mizuna), directly pouring water from above will result in massive leakage; we have fabricated (using a Stratasys 3D printer) rudimentary cases to prevent this. (This is unnecessary if installing gardens in places where water leakage is acceptable.)

The watering process is no different from that for standard gardens, and only involves periodically (in our case roughly once a day) giving water mixed with a commercially available nutrient solution. There is not much subtlety or nuance in the process, and our gardens have thrived even though the amount of nutrients we had given were based on rough estimates,

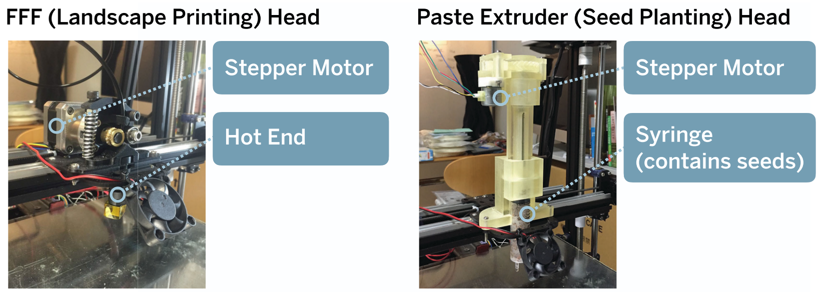

Figure 5: Multi-material garden printer.

and our watering schedules had often been disrupted with business trips, vacations, etc. We have also experimented with placing the gardens under both direct sunlight and artificial light (and in the latter case, experimented with turning on the lights for different hours of the day); although there were some slight differences in growth speed, we found plants to grow healthily as long as they received enough exposure to some form of lighting. All in all, the common herbs we used in our experimentations all showed good growth, eventually becoming large enough for harvesting.

Yarn-based printing has the benefit of using only a single material (yarn) that simplifies the entire process, but also has two major drawbacks. One is the lack of precision; printed felt landscapes typically become bloated (in all 3 directions, although the effect is larger in the *xy* directions) compared to the input 3D model, and it is also impossible to render fine 3D geometries. The second is the lack of scalability, which stems from both the aforementioned bloating (which becomes more of a problem with larger models) and the excruciatingly slow printing speed. Our impression is that printing anything taller than around 20cm is highly impractical using this technique, and thus the use of yarn-based printing is limited to miniature gardens to be placed on shelves, tables, etc.

Multi-Material Garden Printing

The second technique uses not a single material, but a combination of three different materials, namely: thermoplastic (for the outer shell), clay pellets (to fill the interiors), and superabsorbent polymer.

Figure 5 shows the printer. Printing the thermoplastic outer shell is done using a standard FFF head, and planting seeds is done using a standard paste extrusion head, similar to that used in Fab@Home. Again, we need to swap heads during the fabrication process. The seed planting head extrudes a mixture of plant seeds, water, and superabsorbent polymer; unfortunately, in our current implementation the head (or more precisely, the syringe attached to the head) can only hold a single type of seed at one time, and thus to fabricate gardens with multiple types of plants we need to swap the syringe for every type of seed that will be planted onto the landscape. As with the yarn-based printer, this inconvenience is only applicable to our bare-bones implementation—the issue can be avoided altogether if we use a printer large enough to hold multiple heads simultaneously (see Figure 9).

Figure 6 illustrates the roles of the three materials. The outer shell is printed to have a porous mesh structure and filled with clay pellets, which currently we pour by hand during fabrication (we should be able to automate this by installing an additional, dedicated head). After the shell has been printed, plant seeds covered with superabsorbent polymer are extruded onto its surface.

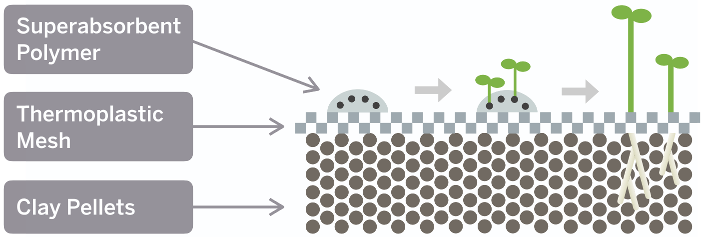

Figure 6: Roles of the three materials in the mixed-material garden.

Figure 7: Multi-material gardens with PLA shell (left), LAY-FELT shell (right).

The important fact here is that the thermoplastic (we used PLA) mesh by itself is a poor substrate due to its porous structure not being fine enough to possess good water-holding capacities; the two other materials are used to complement this poor performance. When the seeds are planted, initially the polymer supplies them with the moisture needed for germination, and after they sprout successfully and their roots begin to reach the shell's internals, the clay pellets start to function as the primary supplier of water. (In time, the polymer gets washed away from the garden's surface.) In effect, the plants will have ample access to water both before and after germination.

Through a series of experiments, we have observed the effectiveness of the above setup—but only to an extent. As can be seen in Figure 7 (left), the rate of successful germination was rather low. We hypothesized that a moderate increase in the outer shell's water-retention capability would alleviate the issue, and experimented with printing parts of the shell using POROLAY LAY-FELT, a specialized filament that can produce objects with microscopic holes on the surface that retain water. This led to much better results as can be seen in Figure 7 (right), but in terms of reliable plant growth, yarn-based printing still has a significant edge. The PLA/LAY-FELT setup gave satisfactory results for some herbs like arugula, mizuna, and watercress, but not for others such as basil and parsley. It appears that the coarseness and patterning of the mesh structure need to be adjusted locally depending on the plant type, to accommodate for differences in seed size, stem/root width, etc., unlike yarn which proved highly conducive sans any adjustments to almost every type of plant we experimented with.

The primary advantages of the multi-material technique are its scalability and speed, both nontrivial issues that hinder the practicality of the yarn-based printer. The thermoplastic structure can also be expected to last and retain its form much longer compared to yarn. The main drawbacks are the lower rate of successful plant growth, and also the environmental cost; the materials used are not as environmentally friendly as yarn, especially due to the superabsorbent polymer which is not biodegradable (we tried using seaweed-derived sodium alginate as a possible replacement, but have so far failed to get good results).

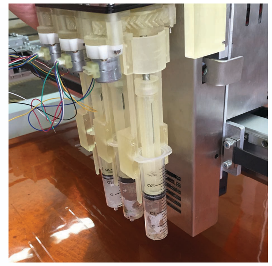

Figure 8: Large-scale printer (left), multi-syringe seed planting head prototype (right).

We are currently experimenting with scaling up this technique, using the BigRep.ONE large-scale FFF printer (Figure 8). In theory, the multi-material technique should work with minimal changes from the MendelMax implementation. We plan to fabricate gardens of up to 1 cubic meter in size, which can be joined together to create even larger, architectural-scale printed gardens.

Future Possibilities

Hydroponics is a highly scalable technology that is used both for small, palm-sized gardens, and also for huge vertical gardens and rooftop farms. It is also versatile, and many types of herbs, fruits, vegetables, and trees are grown using the technology. In principle, this same versatility should apply to printed hydroponics as well. If printing large-scale hydroponic gardens become reality, it could potentially offer a new way of adding greenery to cities, possibly contributing to higher biodiversity, decreased CO_2 levels, mitigation of heat island effect, etc. The mixed-material technique offers a promising path towards this goal. The yarn-based technique, on the other hand, is likely not applicable to such large scales, but its environmental-friendliness and distinct aesthetics could be ideal for creating small-scale gardens for domestic environments.

In addition to scale, we can also think about increasing the complexity of the gardens; whether it would be possible to print more *holistic natural environments* instead of the simple gardens we have been printing using the two techniques. For example, there is already a wealth of zoological knowledge regarding the precise environmental conditions that need to be met for certain animals to thrive. Using such knowledge, we may be able to fabricate artificial environments that are specifically targeted to attract certain animals—for example, a printed garden with a freshwater pond filled with waterweeds may successfully serve as a haven for fireflies. If such gardens become deployed in mass scale, we may perhaps be able to reintroduce animals that had long been chased away from urban centers.

The pursuit of printable gardens can be regarded as part of an eclectic, emerging range of efforts targeting *the realization of habitable bits* [18, 19]—i.e., the post-UbiComp agenda of endowing the built environment with the plasticity and interactivity of digital media. Ultimately, we envision a future where people can take a DIY/participatory approach towards the creation of natural and semi-natural environments, both indoors and outdoors. Through printable gardens, we hope to realize a future where citizens collectively and spontaneously design the *urban ecosystem*, in a way similar to how online volunteers edit Wikipedia articles.

Conclusion

In this paper we have introduced the concept of 3D printable hydroponic gardens, and described our early explorations that primarily deal with material selection.

We have described two techniques that have yielded moderate success: the yarn-based technique and the multi-material technique. Both techniques should be easy to replicate as they rely on relatively simple hacks to a common FFF 3D printer, and we hope this work can kick-start a wave of new investigations to find better-performing materials. Although our efforts so far only amount to small initial steps, printable garden is a concept with a wide latitude for further extensions, making for both an interesting research direction and also a potentially powerful tool for increasing greenery and biodiversity in urban areas.

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