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Integrating soil 3D printing and botanical science for urban agriculture

Nof Nathansohn[1,2], Elisheva Gillis[1], Yuval Ayali[1], Gitit Linker[1], Tomer Faraj[3], Dikla Lifshitz[3], Dagan Bakun-Mazor[4], Einav Mayzlish-Gati[3]
[1]Negev School of Architecture, SCE – Shamoon College of Engineering [2]Massachusetts Institute of Technology [3] The National Genetic Resources and Seed Quality Center, Israel Gene Bank, Agricultural Research Organization, Volcani Center [4]Department of Civil Engineering, SCE – Shamoon College of Engineering, Israel
[1]nof@mit.edu,ORCID 0000-0003-0496-0554

Abstract. This research harmonizes the precision of 3D printing with the vitality of botanical science to envision sustainable urban farming systems rooted in the earth itself. This is a collaboration between architects, computational designers and agronomists, harnessing soil, natural binders, and seeds, to create life-supporting structures that address the interconnected challenges of food security, genetic conservation and ecological construction techniques. During this research, two large scale architectural elements consisted of 18 different objects were 3D printed using a robotic arm to bring this vision to life: a vertical farming structure for wheat germination, emphasizing in situ conservation, and a vegetable garden cultivated to full maturity. The findings reveal how material composition, parametric design and geometry optimization significantly influence moisture retention, structural stability and germination success. This innovative approach delivers a scalable, eco-friendly new vision for urban agriculture and landscape architecture, reducing land use and advancing conservation efforts through the seamless integration of digital design and fabrication and agronomy, reshaping sustainable architecture and agriculture.

Keywords. Urban farming, 3D printing, Bio printing, Soil 3D Printing

1. Introduction

Throughout history, landscape architecture has consistently embraced new technologies and innovative ideas. Landscape design has served as a medium to express not only aesthetic concepts but also ideological perspectives, ranging from the sublime to the practical. From the advanced irrigation systems of the Hanging Gardens of Babylon to the meticulously planned gardens of Versailles, these spaces have reflected human ingenuity and the technological mastery of nature.

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In recent years, the challenges posed by climate change have prompted a revaluation of industrial practices. By 2050, the global population is projected to increase by over 25% (Desa, 2017). To meet the resulting food security demands, current food production rates must increase by 70% (UN, 2024). The increasing need to maintain food security requires solutions that both involve breeding resilient crops that can withstand the challenges of climate change while maintaining high yield levels and increasing crop yields by expanding the amount of land used for agriculture. Currently, the global agricultural sector uses over 17.84 million km^2 of land. Although there is a need for increased land use, further expansion would place significant strain on the environment (Xi et al., 2022). Genetic diversity from sources such as wild relatives and landraces, is essential for developing climate-resilient crops. These genetic resources provide a reservoir of traits that can enhance stress tolerance and adaptability to changing environment. Genetic diversity conservation is a significant concern, with two primary approaches: ex situ and in situ, both are equally important and should be seen as complementary (Dulloo et al., 2010).

Ex situ conservation involves preserving genetic diversity outside natural habitats, typically by storing seeds, live plants, or tissues and cell cultures in gene banks. In situ conservation focuses on maintaining biodiversity within its natural environments—the wild nature for wild plants or "on-farms" for domesticated or cultivated species (UNCED, 1992). *In situ* conservation enables evolutionary processes by exposing plants to biotic and abiotic factors in their natural habitats. This exposure helps establish the adaptive abilities of the plants. These evolutionary processes enrich traits and biodiversity, which ultimately benefit agricultural cultivation. Urban farming, also referred to as urban agriculture, can address both the conservation of genetic diversity and the reduction of land use. Recently, urban farming practices have been utilised for conservation, particularly as an alternative to *in situ* conservation. To reduce land use, incorporating various urban farming practices such as rooftop gardening, community gardens, vertical farming and container farming (Al-Kodmany, 2018) can significantly increase the supply of fresh, locally grown produce to urban residents. This approach shortens the distance food travels from farm to table, thereby lowering carbon emissions. Additionally, it enhances food accessibility and affordability, addressing undernutrition among urban populations (Siegner et al., 2018; Satterthwaite et al., 2010). This research is a collaborative involving architects, computational designers, and agronomists. It aims to explore the intersection of precise machines and the unpredictability of nature to develop innovative urban farming practices, as was successfully tested with two full scale study cases (Figure 1 shows study case 1: Totem).

The use of earth as a construction material has been a vernacular practice since around 10,000 BC in Mesopotamia. Its benefits lie in its abundance, accessibility, affordability, and local availability (Gomaa et al., 2022). Today, given the undeniable environmental effects of construction, it is crucial to adapt and reinvent earth as a construction material. Historically, earth was used in construction through techniques like compressed earth blocks, adobe, cob and rammed earth walls. These traditional building techniques require highly skilled builders, and they are often being left aside as modernised building practices are faster and cheaper. With advancements in technology, some of these processes have been modernised, creating a hybrid approach

Figure 1. Totem, 2023, One week after printing

Figure 2. One Month after printing.

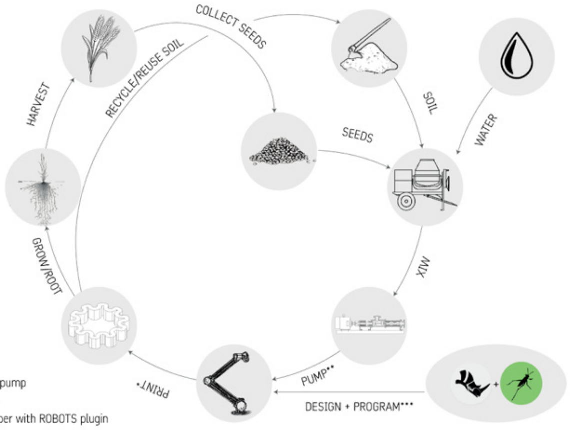
that combines traditional materials with innovative design processes (Ji et al., 2023). One such innovation is 3D printing. The advantages of 3D printing in construction are significant. It enables material reduction, geometric complexity, and design freedom, while lowering labour costs and reducing construction time. However, achieving material consistency is critical, as the texture must allow for successful extrusion and layering (Gomaa et al., 2022).

This research harness technological advancements and digital fabrication to support urban farming structures and the growth of plants in the built environment. To do so, we developed a custom-built machine capable of 3D-printing large-scale gardens using soil and seeds (Figure 2). This process integrates computational workflows to optimise plant growth conditions and design geometries that support germination and development. Once printed, the structures evolve organically as seeds germinate and transform the digitally designed framework (Figure 3). The success of this research relies on the material composition: one that is stable for 3D printing, but is also airy to support growth of plants. 3D-printed gardens represent a novel approach to urban farming, offering a sustainable solution for growing food in densely populated areas. After harvesting, the structures can support further plant growth through hydroseeding, ensuring a sustainable approach.

2. Methodology

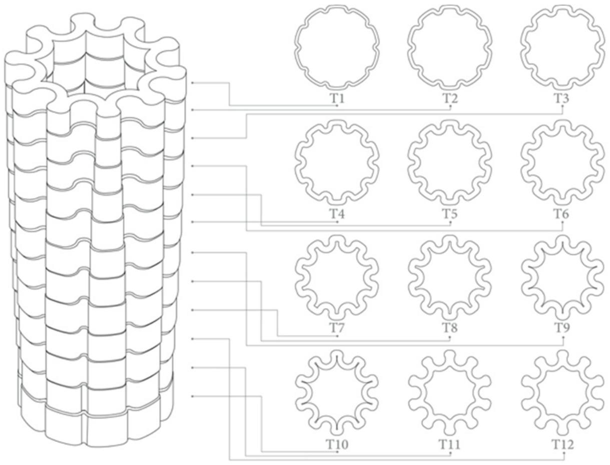
2.1 MATERIAL DEVELOPMENT

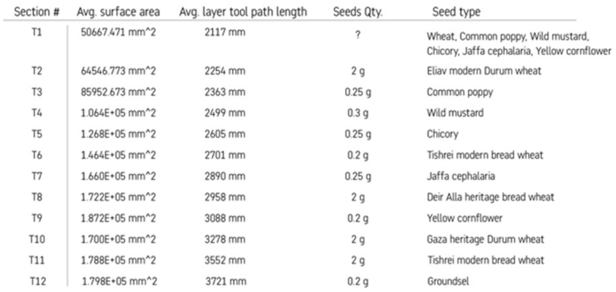
Following Nathansohn et al. (2024) for machine construction and 3D printing, we further tested earth structure mixtures to identify materials that support plant growth while maintaining strength. We evaluated combinations of soil, fibres, natural binders, and plant nutrients, considering both construction strength and agronomic needs for a fully mature vegetable garden at full scale (Table 1 shows Totem study case, Table 2 shows Digital Gardens study case). The components of the soil-based material were mixed in a 200-litre cement mixer in batches of 49 to 53.45 litres. To prepare the printing material, 16.5 to 27.5 parts soil, 0 to 11 parts fibres, 8 parts Moza clay, 12 parts water, 0 to 2.45 parts sawdust, and 1.5 parts organic fertiliser were gradually and intermittently added to the mixer to form a firm, pasty textured material. Different types



*Kaleta-150 Plaster pump
**UR10 robotic arm
***Rhino + Grasshopper with ROBOTS plugin

Figure 3. Circular and local fabrication process was implemented





Section #	Avg. surface area	Avg. layer tool path length	Seeds Qty.	Seed type
T1	50667.471 mm^2	2117 mm	?	Wheat, Common poppy, Wild mustard, Chicory, Jaffa cephalaria, Yellow cornflower
T2	64546.773 mm^2	2254 mm	2 g	Eliav modern Durum wheat
T3	85952.673 mm^2	2363 mm	0.25 g	Common poppy
T4	1.064E+05 mm^2	2499 mm	0.3 g	Wild mustard
T5	1.268E+05 mm^2	2605 mm	0.25 g	Chicory
T6	1.464E+05 mm^2	2701 mm	0.2 g	Tishrei modern bread wheat
T7	1.660E+05 mm^2	2890 mm	0.25 g	Jaffa cephalaria
T8	1.722E+05 mm^2	2958 mm	2 g	Deir Alla heritage bread wheat
T9	1.872E+05 mm^2	3088 mm	0.2 g	Yellow cornflower
T10	1.700E+05 mm^2	3278 mm	2 g	Gaza heritage Durum wheat
T11	1.788E+05 mm^2	3552 mm	2 g	Tishrei modern bread wheat
T12	1.798E+05 mm^2	3721 mm	0.2 g	Groundsel

Figure 4. Design and Fabrication Data for Totem

of seeds were then incorporated into the paste, with each type tested in a separate batch. Small seeds were added at 0.025 parts, while larger seeds, such as beans, were added at 2 parts.

2.2 PARAMETRIC DESIGN AND 3D PRINTING

The printing process was carried out using an assembled system that included a plaster pump connected to a plaster pipe mounted on a Universal UR10 robotic arm with a custom-made end effector featuring a 40mm nozzle. After mixing, the material was fed into the pump and extruded through the nozzle, following a G-code generated with the Grasshopper plug-in for Rhino. Three different modules were printed using various seed species and material recipes to evaluate how different geometries influenced plant growth. In total, 18 full-scale elements were produced, incorporating a variety of wild plants, landraces and modern wheat, cucumbers, green beans, and tomatoes. During printing, the machine operated with a pump speed adjusted to 35-36 litres per minute and the robotic arm set to 50mm/s. The printing layer height was adjusted to 8mm, and due to the nozzle's 20mm diameter, the layers were pressed on top of each other, resulting in a printed material width of 40mm-60mm (figure 4). In order to achieve stability, the layers were printed with an overlap and only a relatively small offset. The printed shapes were designed with sharp curves which also contributed to their stability. (figure 5).


Figure 5. 3D printed Saint Pierre Burbank tomato brick, 4 weeks post printing


Figure 6. Module T6 of Totem, with Tishrei modernise wheat

2.3 EXPERIMENTS LAYOUT

2.3.1 Outdoor Study case, "Totem"

This large-scale soil and seeds 3D printing object was commissioned for an outdoor art exhibition in fall 2023. The selected seeds included landraces and modern wheat varieties from the Israel Gene Bank (IGB) collection. This specific printing explores the potential of vertical planting for in-situ "on-farm" conservation of important landrace genetic material and examines the potential for vertical growth of wheat in urban farming conditions. Multiple species of native wildflowers were also tested in the experiment, but only Papaver rhoeas germinated. The printing was 1800 mm height and 900 mm width, comprising nine different modules (Figure 6) with varying geometries and seed types. This object, supported by an inner steel skeleton, was placed outdoors. To achieve a structurally sound design, the geometries were optimised for maximum stability. Minimal variations between the layers - such as scaling down from the centre at each layer by 8%-10% - facilitated the attainment of maximum object height and enabled the stacking of extruded elements. The emphasis on seed germination and growth dictated the structure. Aerated structures - with minimal touching surfaces in plan - were designed to leave enough space for the seeds to germinate and develop, as well as for air and water circulation

Table 1. Material compositions of Totem Experiment

	Seed Type	Soil % weight	Clay % weight	Water % weight	Sawdust % weight	fertiliser % weight	Seeds % weight
T1	Common poppy, Chicory, Yellow cornflower	NC	NC	NC	NC	NC	NC
T2	Eliav Modern Durum Wheat	29.904	26.582	36.248	0.397	2.039	4.833
T3	Common poppy *(Papaver rhoeas)*	31.420	27.929	38.085	0.415	2.142	0.008
T4	wild mustard *(Sinapis arvensis)*	31.420	27.929	38.085	0.414	2.142	0.009
T5	Chicory *(Cichorium intybus)*	31.420	27.929	38.085	0.415	2.142	0.008
T6	Tishrei Modern Bread Wheat	29.904	26.582	36.248	0.397	2.039	4.833
T7	Jaffa Cephalaria *(Cephalaria joppensis)*	31.420	27.929	38.085	0.415	2.142	0.008
T8	Deir Alla Heritage Bread Wheat	29.904	26.582	36.248	0.397	2.039	4.833
T9	Yellow cornflower *(Chrysanthemum segetum)*	31.421	27.930	38.086	0.415	2.142	0.006
T10	Gaza Heritage Durum Wheat	29.904	26.582	36.248	0.397	2.039	4.833
T11	Tishrei Modern Bread Wheat	29.904	26.582	36.248	0.397	2.039	4.833
T12	Groundsel *(Senecio)*	31.421	27.930	38.086	0.415	2.142	0.006

Table 2. Material compositions of Digital Gardens Experiment

Seed Type	Soil % weight	Coconut fibres % weight	Clay % weight	Water % weight	fertiliser % weight	Seeds % weight
Beit Alpha Cucumber	20.821	3.856	30.846	42.062	2.366	0.049
Jaguar green beans	20.811	3.854	30.831	42.042	2.365	0.098
Saint Pierre - Burbank tomato	20.829	3.857	30.858	42.079	2.367	0.011

2.3.2 Indoor Study case, "Digital Gardens"

The potential for full growth and harvesting within a controlled environment was tested during summer 2024. The design process relied on computational workflows to predict the optimal conditions for plant growth and used this data to design geometries that support development. Three different modules were printed using seeds of three species (cucumbers, green beans and tomatoes) and the same material recipes to assess how different geometries contributed to plant growth. In total, nine full-scale printed objects elements were produced including bricks (250mm wide, 450mm long, and 180mm high as shown in Figure 7) and arched walls with a diameter of 1000mm.

Figure 7. Cucumber brick, 1 month post printing (left) and 2 months post printing (right)

The growth period took place in a controlled environment, allowing the testing of different geometries and structures and their impact on the developed plants. The experiment was set in a greenhouse with natural light and controlled temperatures and irrigation. Briefly, the growth chamber was maintained at 25°C, and irrigation was conducted using sprinkler irrigation four times during the day, each lasting for two minutes. During the growing period, the plants were closely monitored and measured. The number of sprouts was counted to assess the seeds' ability to germinate within the printed structure. Additionally, the plants were observed throughout their growth to evaluate whether the seedlings matured, survived, and produced yield.

3. Results and Discussion

3.1 PLANT GROWTH

In Totem, the geometry and design seemed to affect wheat growth. The mid-height geometries, which were designed to have larger offsets between layers and larger inserts (curved arches), showed more growth, as they were accumulating more moisture and drying slower. Some of the landrace wheat varieties reached a height of 25 cm after a few weeks, sporting awns on top that held potential for harvesting for bread making.

To examine these phenomena the printed objects for the second-monitored experiment were designed with two different geometries: a very curved enclosed brick and an arch with inserts. During this phase of the research, the brick geometry proved more successful than the arch in facilitating rapid full-scale garden growth. Its denser structure retained moisture more effectively than the other modules. In two different designs with the same material volume and number of seeds, one geometry enabled 2.6 times more growth (139 vs. 53 cucumber sprouts two weeks after printing out of about 7 grams of seeds that were printed, equivalent to about 200 seeds). Two tomato bricks had 43 and 37 sprouts two weeks after printing, while the arch had only 29 sprouts, both out of 3 grams of seeds that were extruded, equivalent to about 600 seeds. The green bean brick and arch produced only a small number of sprouts, 7 and 8 respectively. This is likely because green beans are typically planted on the surface of the soil rather than buried. As a result, the bean structures only grew on the outer top layer. Post-fabrication, the majority of growth was seen in the gaps between the extruded material. Ultimately, all the walls and bricks produced fully-grown vegetable gardens.

3.2 MATERIAL STRENGTH

Understanding the structural performance of the printed objects is crucial for vertical farming applications, as it directly impacts the maximum achievable height and number of growing layers that can be safely stacked. To evaluate the strength, the bricks were subjected to two treatments: they were either left to dry immediately without watering or watered regularly. The objects that were not watered failed to grow but began hardening a few days after printing. After harvesting, the bricks that did grow were no longer watered and were allowed to dry to enhance their strength. Their strength was tested one month after last watering.

The test performed was a load test to evaluate the stress-strain performance of the material. The stress-strain graph in Figure 8 from the left corresponds to a brick that was watered and supported the full growth of wheat. The material exhibited elastic behaviour with a linear increase in stress, followed by a yield point at 10% strain, indicating the transition to plastic deformation. The material demonstrated ductility, with high strain values before reaching failure, which is characteristic of earth-based materials. The total load it was able to carry before failure was 2.5 MPa. The graph in the right corresponds to a brick that was not watered. The stress increases linearly with strain, indicating elastic behaviour. The peak stress, 1.8 MPa, marks the material's maximum load-bearing capacity. After this point, the stress decreases slightly, suggesting material softening or failure. The graph indicates moderate ductility. The soil strength obtained can support a soil column of several tens of meters. If we assume a (conservative) soil density value of 2.0 grams/cm^3, then a uniaxial compressive strength of 1.8 MPa can support a soil column of 90 m in height before reaching compressive failure.

3.3 LIMITATIONS

Testing the materials in a controlled environment presents challenges when plants are involved. The watering and lighting conditions of the objects had to be frequently adjusted, and the greenhouse was too small to accommodate the printing process. As a result, some of the samples were damaged in transportation. That said, the goal is to develop a method to print, grow, and harvest—all within a single site, eliminating the need for transportation. The ability of the material to support wheat growth in an uncontrolled environment was a success, as it better replicates the conditions in which urban farming typically occurs. To construct taller structures, printing would need to be carried out over several days, with pauses every 20-30 layers to allow the material to harden enough to support additional layers. Simultaneously, the material must remain slightly wet.

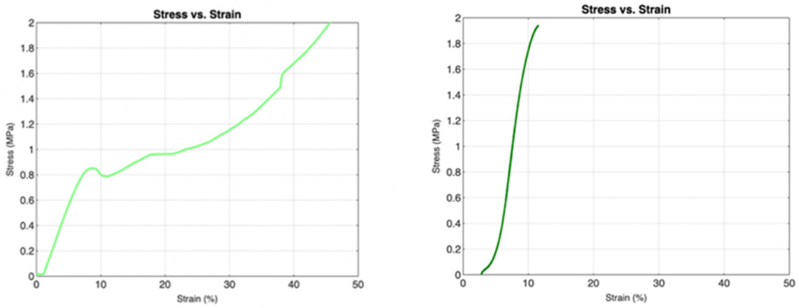


Figure 8. Stress-Strain graph for a wheat brick (left) and for an ungerminated brick (right).

4. Conclusion

This research demonstrates the potential of integrating digital fabrication with agronomy to create innovative and sustainable architecture and urban farming objects. By developing a custom 3D-printing process that utilises soil-based materials embedded with seeds from different sources, the study successfully produced structures that not only serve as functional garden elements but also promote the growth of a variety of plant species. The results highlight the effectiveness of certain geometries in optimising plant growth, particularly in moisture retention, which is critical for the success of vertical agriculture. The ability to cultivate fully mature gardens in controlled environments suggests promising applications for urban agriculture and the preservation of genetic resources.

The incorporation of plants into the built environment contributes to reducing carbon emissions, improving air quality, and mitigating the urban heat island effect. Green elements also enhance urban biodiversity and create wildlife habitats. While the study achieved promising results, challenges remain in balancing structural integrity with the conditions required for plant growth.

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