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Article

# Open-Source Indoor Horizontal Grow Structure Designs

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**Abstract:** Agrivoltaic agrotunnels are currently designed for high density grow walls that are not amenable to bush berries or root crops. Commercial grow bins provide deeper substrates for produce with more root systems but have high costs per unit growing area. To overcome the economic limitations of grow bins, this study applies the distributed manufacturing open-source design paradigm to develop four designs for low-cost open source structures. The designs target root vegetables and bush fruit specifically to be adopted by remote communities with limited or no outdoor growing environment to offset the market price for imported fresh produce. The indoor growing designs provide the necessary structure for supporting grow light and grow bins and enabled the transplanted berry plants to flower and produced fruits. They provide a comparable amount (110L) or more of grow volume from 106 to 192 L. The water reservoir volume for the commercial system (62 L) and grow area (0.5 m<sup>3</sup>) is surpassed by all new designs that range from 64 to 192 L and 0.51 to 0.76 m<sup>3</sup>, respectively. These superior properties are possible with material costs for all four designs that save more than 90% of the economic cost of the commercial systems.

**Keywords:** indoor growing; grow bins; aeroponic; hydroponic; mechanical design; distributed fabrication; open hardware; controlled environmental agriculture; sustainable agriculture; agriculture

## 1. Introduction

With rapid population growth [1] and global climate destabilization [2,3], there has also been a growing focus on unconventional agricultural farming [4,5]. Studies done in Ghana shows that the current trend of urbanization in global south is driving farmers along with arable land away from the condensed urban population [6], which subsequently impose additional cost to both suppliers and consumers on storage facilities and transportation of food [7]. In Kampala, Uganda, continued urbanization is expected to influence low-income households the most [8]. Studies on spatial location of new supermarkets done in another global south city Lusaka, Zambia, suggests that the development of urbanization and supermarkets favors areas that are already more food-secured, further burdening the low-income population [9].

Indoor growing, which has recently been industrialized [10–13], has been practiced mostly for decoration purposes for centuries [14]. It has been proposed by many authors [15,16] and to a lesser extent by commercial entities, to adapt it from distributed production of food within the home [17,18]. This new method of agricultural production is especially relevant for remote communities [19–22], and regions under extreme weather conditions where outdoor growing is challenging or nearly impossible [23,24]. Unfortunately, with climate change these relatively extreme conditions are expected to grow in the future [25,26]. Even for areas where outdoor agricultural farming is frequently practiced, the increased rate of unpredictable weather could still threaten local food security, passively raising daily produce prices. Therefore, the potential to achieve growing produce

year-round at home is attractive especially for regions when market prices are high and usually coupled with inferior qualities [27,28] or have recently been affected by price spikes [29].

Indoor growing is comprised of several types of technical systems: lighting, water/nutrients, growing media, air quality and crop maintenance. Optimal lighting involves altering both the spectrum and intensity of light for specific crops [30,31]. With reduced arable lands, conventional cultivation method using soil [32] is transitioning to soil-less cultivation methods [33,34] such as hydroponics, aeroponics, and aquaponics [35] or a mixture of two or more methods under controlled environment. Soil-less system includes the use of alternatives substrates such as rock-wool to support the roots in liquid nutrients [33]), and in the case of aeroponics, roots can be completely exposed to the air.

Indoor growing environments tend to have carefully controlled temperatures that can be done passively [36] or actively [37] as well as humidity control [38]. The active systems can adjust the speed of ventilation. Finally, for handling farming operations like planting, pollination, pruning and harvesting the systems can be manual or use various types of electronics and automation [39,40] to monitor and adjust the conditions of growing environment (e.g., temperature, moisture, and pH).

In general, indoor growing has several advantages in common: i) climate control (temperature, humidity, lighting, airflow) [41,42], ii) pest control [38,43], which in turn minimizes the need for harmful chemicals [44] (although it should be noted that if pests invade controlled environments they can be challenging to eliminate as there are no natural predators available [45]), iii) high water [44] and space efficiency [46] compared to conventional farming, iii) reduced transportation economic and environmental costs as it can be localized [47], which also provides higher nutrient density [30]; iv) all year-round production and yield consistency [30,41].

Due to these many advantages, there are several crops that are commonly produced in doors: leafy greens [48,49] mushrooms [50], tomatoes [51], strawberries [52], and herbs [49]. These crops have been shown to be amenable to indoor growing including manageable plant and root system size, low pollination requirements and shorter growth duration. On the other hand, several crops not commonly grown indoors include corn, root vegetables, grapes, grains and fruit trees (e.g., apples, oranges as heavy duty machines are commonly used to harvest the fruits, which are less suitable for indoor operations [53].

In order to service remote communities with indoor agriculture many novel designs based on containers have been proposed [54,55]. Many container structures used for indoor growing also have relatively poor insulation because adding insulation reduces grow volume, which makes them susceptible to large temperature fluctuations and/or large energy use [56,57]. The latter has resulted in poor economic performance [58].

A recent approach that seeks to overcome the weaknesses of containers is the concept of an agrivoltaic agrotunnel. Agrivoltaics is the colocation of agriculture and solar photovoltaic (PV) production [59]. The first agrivoltaics agrotunnel [60] used variable tilt PV [61] on the outside that grow crops underneath them to power the pumps, heat pumps and grow lights on the inside. Various types of PV arrays can be used for agrivoltaics that depend on the specific outdoor crop including conventional fixed tilt [62,63], stilt-based systems[64,65], trellis systems[64–66], fences[69–71], single axis trackers[72,73], fixed vertical [74–76] and wind-adjusted vertical systems[77,78]. The agrivoltaics agrotunnel concept enables net zero food energy production of indoor food because the PV generation can be matched to the energy needs of the indoors. Outdoor agrivoltaics has been shown to increase yields for a wide variety of crops such as kale, chard, broccoli, pepper, tomatoes, spinach [79], celeriac [80], lettuces [81], and basil [82] as well as reducing the amount of carbon emissions [83–85]. Agrotunnels are modular, can be placed near the consumers to reduce food miles, and allow for climate control, year-round production just like other indoor systems. The higher density achieved with vertical grow wall design enables economic production [60] and can even be built underground for better temperature control and resilience to extreme weather.

The agrotunnel is currently designed for high density grow walls. These walls can be used to grow common crops such as herbs, lettuces, kale and other leafy greens as well as strawberries; however, they are not amenable to bush berries or root crops like potatoes. Grow bins (see Figure 1)

enable remote communities with no or limited access to fresh produce (especially potatoes) as they provide deeper substrates for produce with more root systems. Figure 1 is a commercial growbin with a retail cost of \$4,500, which makes it financially unviable for all but the most expensive crops.



**Figure 1.** Commercial grow bin.

In order to overcome the primarily economic limitations of conventional grow bins, this study applies the distributed manufacturing open-source design principles [86,87], to develop low cost open source grow bins for agrotunnels, which can also be used for indoor growing at home. Four designs will be constructed and assessed including the commercial comparison. Open-source designs will target achieving the similar growing capacity and functionality while minimizing the cost of building the system. The performances of the open-source designs will be assessed by transplanting berry plants into them and observe the growth progress of the plants along with the berry plants in the commercial grow bin. Properties of the open-sources designs will be numerically compared to each other and the commercial product for assessment, such as prices of the materials used, growing volume and area, volume of water (nutrient solution) reservoir, percent savings of cost per growing surface area compared to the commercial product, assembly difficulty, and the rigidity of the

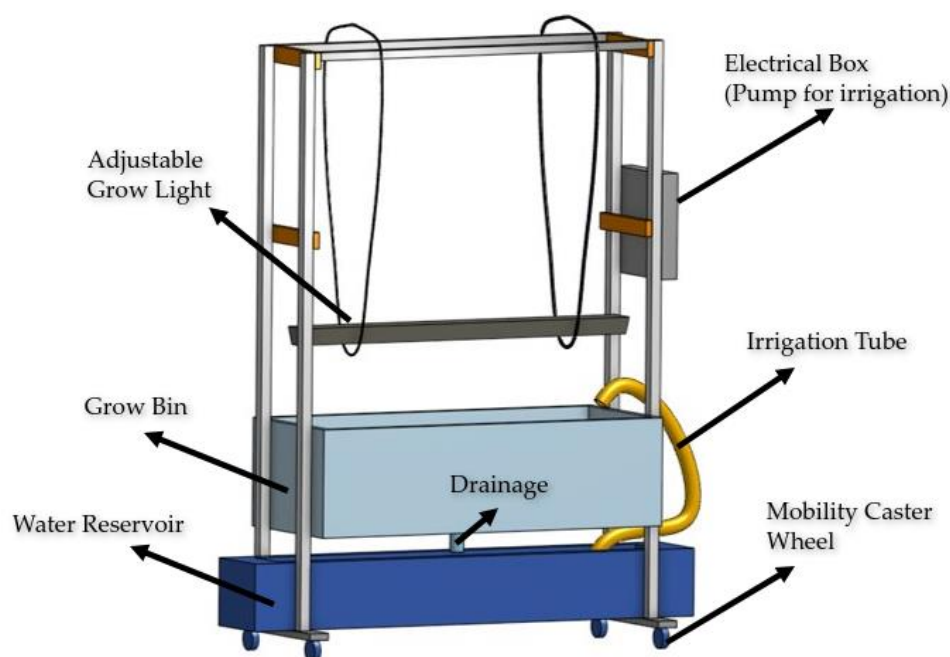
structures when being moved. This article will present four conceptual designs for grow bins targeting root vegetables and bush fruit specifically to be adopted by remote communities (poor or harsh weather) with limited or no outdoor growing environment to offset the market price for imported fresh produce.

## 2. Materials and Methods

### 2.1. Design Criteria

The structure shown in Figure 1 allows users to either put the plants and substrates straight into the container volume, or a mesh grow bag can be suspended inside the container to allow better air circulation for the plants. Size of used mesh bag is used to estimate the yield assuming potatoes are planted inside. The mesh bag is 106.68 cm long, 25.40 cm deep, and 40.64 cm wide. With this volume (0.1 cubic meters) and depth, 3 potato plants can be planted following conventional guideline of 25 to 30 cm of in-row spacing [88]. These structures are generally not viable to grow crops like potatoes. Consider, it takes 70 to 120 days for potatoes to be ready for harvest depending on the varieties [89], which is 3 to 4 harvests a year if grown indoors. Each harvest can potentially yield 8.1 to 9.3 kg [90], yield per year will then be 24.3 to 37.2 kg. Price of potatoes in Ontario, CA is CAD\$1.12 per lb. (CAD\$2.5 per kg) [91]. Following this calculation, one can produce CAD\$60 to CAD\$93 worth of potatoes per year, which will take 48 to 74 years to recover the cost of purchasing a commercial grow bin even if all operating and labor costs are ignored.

The commercially available grow bin (Figure 1) is rendered with annotations in Figure 2.



**Figure 2.** Overview of Commercial Grow Bin System.

The design criteria for grow bins to replace the commercial grow bin. The main components are the planter bin that holds the crop with substrates and the reservoir bin that stores drained water from the planter bin. A submersible pump is used to deliver nutrient solution from the reservoir bin to the planter bin, controlled by a timer with adjustable frequency. The frame is optional if users can support the grow light by other means such as suspending the light from the ceiling if available. The vertical height of the structures (around 1.8 meters tall) is necessary in the tunnel since attachment on the ceiling and wall is prohibited to ensure the integrity of the tunnel structure. The height of the frame is decided by the anticipation of how tall the types of crops planted will reach at their maturity. Similarly, the inclusion of the wheel for mobility is also optional. They are added for cleaning to maintain the environment of the tunnel.

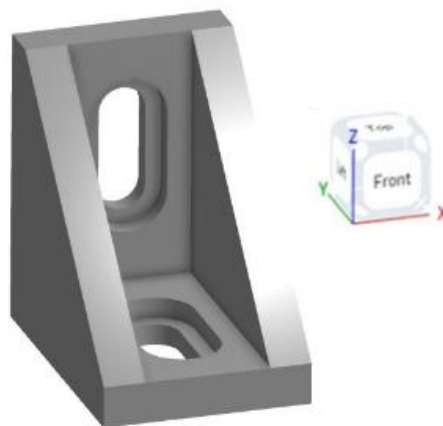
Using Figure 2 as a guide, a functional grow bin should include the following components (bottom to the top):

- Wheels for mobility (optional)
- Water reservoir to collect drainage from grow bin.
- Drainage hole to allow excessive water to drain from grow bin.
- Grow bin to hold substrate and plants.
- Irrigation system to pump reclaimed water back into grow bin.
- Electrical box to control water pump.
- Structure to hold and adjust the height of the grow light as plants grow.

There are four designs aside from the commercial comparison: Inverted T, Boxed Rectangle, Single Water Reservoir, and PVC + Mobile Platform. Specifically, the designs are as accessible globally as possible using an open hardware paradigm [92–95]. This means when possible, using off-the-shelf materials and the use of self-replicating rapid prototype (RepRap) class [96–98] fused filament fabrication-based 3-D printers of varying tolerances and capabilities, which have been shown to radically reduce the costs of a list of products.

The concept behind the first design (Inverted T) is to use as little material as possible to support grow bins and to hang grow light. The rectangular bottom provides a platform for the grow bins to settle. On the top, one aluminum bar is supported by two vertical extrusions to hang the grow light.

Table A1 lists the materials used for the Inverted T structure. Prices are adjusted to the actual amount of materials used based on bulk price from the URLs. 3D printed parts are used whenever possible to offset the prices. Figure 3 shows the rendering of the STL file for the 3DP parts. The cost of the 3DP part is estimated from the amount of filament used in the slicing software [99,100].



**Figure 3.** Rendering of 3DP corner bracket (Print with +Z axis up).

Figure 3 shows the rendering of the corner bracket file, which can be 3D printed to replace the metal ones to offset the cost. Users can modify these to make it larger for stronger connection. Table 3 shows the parameters used for slicing the STL file. Other parameters can remain in default, infill percentage is maximized for material strength. Support is optional.

**Table 3.** Slicing parameters of 3DP corner bracket.

Print Settings			
Layer height	Layer height	0.4 mm	
	First layer height	0.3 mm	
Vertical shells	Perimeters	2	
Horizontal shells	Solid layers	Top	4
		Bottom	3

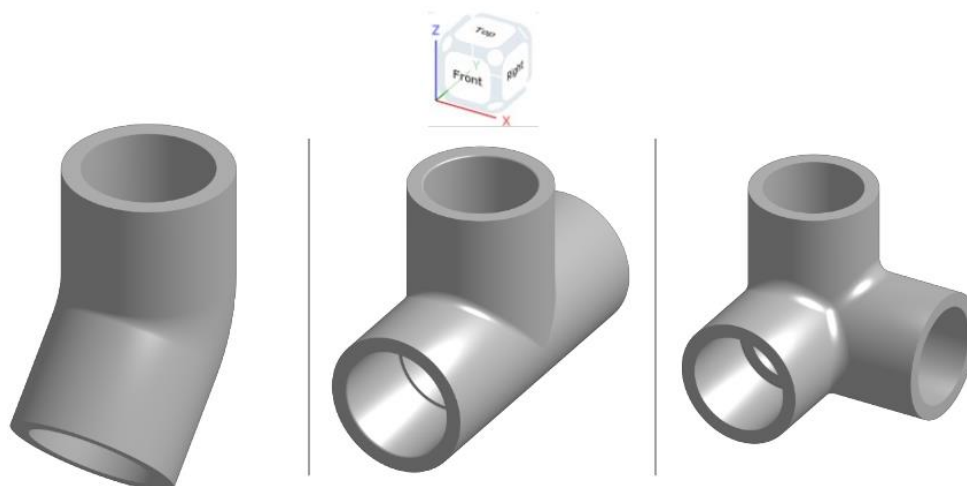
	Minimum shell thickness	Top 1.2 mm Bottom 0.8mm
<b>Infill</b>	Infill Pattern	Rectilinear
	Infill Percentage	100%
	Top fill pattern	Monotonic Lines
	Bottom fill pattern	Monotonic
<b>Skirt and brim</b>	Skirt distance	3 mm
	Brim type	Outer brim only
	Brim width	0 mm
<b>Temperature [PETG]</b>	Nozzle [0.6 mm]	240 °C
	Bed	85 °C
<b>Fan</b>		Automatic
<b>Travel lift height</b>		0.2 mm
<b>Retraction length</b>		1 mm
<b>Max volumetric speed</b>		15 mm <sup>3</sup> /s

The second design (Boxed rectangle) is a strengthened version of the first one. Additional support is added on the side to prevent the grow bins from sliding off the bottom platform. More aluminum extrusions are used for better integrity. Table A2 shows the bill of materials used for this frame.

The third design (Single water reservoir) targets smaller plants with smaller volume grow bins. It uses a single water reservoir for all six grow bins on top. All six grow bins are tilted inward to direct the drainage to the rain gutter placed in the center, which connects to the bottom water reservoir. Table A3 includes the bill of materials for this design.

The idea behind this version (PVC frame) is to separate the platform for supporting grow bins and the structure for hanging the grow light. It is easier to just move the bottom platform with grow bins without the burden of having to move the structure for grow light at the same time. Table A4 shows the bill of materials used. A higher cost saving is realized since more parts can be substituted with 3D printed parts in this case.

Rendered files of 3D printable parts for connecting PVC pipes are shown in Figure 4. Slicing parameters from Table 3 can be used for the PVC pipe fittings, supports are required for the 3-Way Tee Connector and the 3-Way Connector. The 45 Degree Connector can be printed with one end on the bottom to avoid support, while the other two parts should be printed with +Z axis up with supports enabled.



**Figure 4.** 3D printable replacement for PVC frame (From left to right: 45 Degree Connector, 3-Way Tee Connector, and 3-Way Connector).

Aside from frames, there are universal components used in each design for holding plants and irrigation purposes. Table A5 lists the components for single bin design (used in Inverted-T, Boxed-rectangle, and PVC versions), Table A6 lists the extra components for the single water reservoir design.

### 3. Results

Figure 5 presents a simple frame to hold three bins and grow light. Two off-the-shelf bins are stacked together, plants will be potted on the top bin with the bottom bin acting as the nutrient solution reservoir. Grow light is attached onto the top of the frame with customized 3-D printed parts and a pair of adjustable rope hangers.



**Figure 5.** Inverted T structure.

Like the design shown in Figure 5, the design in Figure 6 provides additional side rail support for the grow bins from the side to prevent them from sliding off while moving the whole structure. With both a rectangular shape on top and bottom, the integrity is better than the previous design.



**Figure 6.** Boxed Rectangle *structure*.

Figure 7 is a more refined design for Jellybean blueberry plants that are typically shorter, so the distance between light and the plants can be reduced. It requires some additional work to tilt all the bins to allow liquid to drain into the same water reservoir shown on the bottom of the structure.



**Figure 7.** Single water reservoir structure.

Figure 8 shows a design that separates the structure for holding the grow light and the bottom mobile platform to hold the grow bins. Cost is minimized this way as vertical aluminum profiles are replaced with PVC pipes to support the grow light.



**Figure 8.** PVC + mobile platform *structure*.

Figure 9 shows the fruition or blossoms (for the Jellybean blueberry) of the planted berries. Prior to potting them into the grow bins, these bushes did not carry any flowers. Within one month, with proper nutrient solutions and abundant lights with proper spectrum, these berry bushes started to carry fruits or flowers.



**Figure 9.** Fruition of berries planted.

Table 10 compares the various properties of all the systems presented in this study.

**Table 10.** Grow bin system design comparison.

	<b>Inverted T</b>	<b>Boxed Rectangle</b>	<b>Single Water Reservoir</b>	<b>PVC</b>	<b>Commercial Metal</b>
BOM Cost [CAD\$]	\$201.74	\$331.14	\$379.46	\$293.64	\$4,500.00
Grow volume [L]	Up to 192	Up to 128	Up to 106	Up to 128	Up to 110
Water reservoir volume [L]	Up to 192	Up to 128	Up to 64	Up to 128	Up to 62
Growing surface area [m <sup>2</sup> ]	0.76	0.51	0.60	0.51	0.50
Cost per surface area [CAD\$/m <sup>2</sup> ]	265.45	649.29	632.43	575.76	9000.00
Percent savings of Cost per surface area [%]	97	93	93	94	NA
Assembly difficulty	Low	Low	Medium	Low	High
Rigidity	Low	Medium	Medium High	Low	High

#### 4. Discussion

As can be seen by the results in Table 10, the material costs for all the open-source grow bins are well beneath 10 percent of the cost of the commercial comparison. The Inverted T system represents a 97% savings, which is in line with the savings found for other open source hardware [101]. The cost savings can be further enhanced by 3D printing connection parts, which again is consistent with other studies of distributed additive manufacturing [102,103]. The grow volumes are comparable across the designs. The Inverted T frame has the most volume and houses three stacked bins by not having the side guard rail to prevent them from sliding off the bottom platform. The Single Water Reservoir design has just slightly less grow volume than the commercial system, while all others have a greater volume. All of the open source designs have a greater water reservoir than the commercial system. This is an advantage to allow longer periods without grower intervention to add more water. The Inverted T design, for example, can go roughly three times longer without adding water than the commercial system with the same plants. The growing surface area is greater for all of the open source designs as compared to the commercial system. This makes the cost per growing surface area perhaps the most striking as the commercial system is \$9,000/m<sup>2</sup> and all of the open source systems are under \$650/m<sup>2</sup>.

The assembly difficulty is estimated by the tools needed to complete the frame building. For Inverted T, Boxed Rectangle, and PVC frames, only a screwdriver and a drill are needed aside from cutting the aluminum extrusions into length that can be accomplished with a hacksaw (or can be ordered from vendor to length). The Single Water Reservoir design requires additional sealant for drainage systems and represents the most complicated system to fabricate. Although the commercial system was not evaluated directly as it is purchased, it does demand metal work, which requires higher skill and more costly labor. The rigidity for all the structures are estimated by how manageable it is to move them. With plants, substrates, and water inside the bins, it is difficult to maneuver all the grow bins frames because of the mass. None of the grow bins are, however, intended to be moved often. The mobility of the frames is only required in case of water leakage and cleaning below the frame. For the purpose of growing indoors, they all share very similar functionality. For applications that are not agrivoltaics agrotunnels, when organic material or walls can be utilized, users can separate the support for growing light and the grow bins, which would further reduce costs. The grow bins can be directly placed on the ground instead of offsetting some distance relative to the ground.

In summary, all four of the open-source designs offer competitive if not greater capacity (grow volume, water reservoir volume, and growing surface area) compared to the commercial system. A significant savings (>95%) are realized in the cost per growing surface area. Additional potential savings of 1.95%, 3.07%, and 14.8% is realized by 3D printing applicable parts are included in end of Table A1 (Inverted T), A2 (Boxed Rectangular), and A4 (PVC), respectively.

The open source systems do have some limitations. First, in practice, it is much easier to relocate the commercial system due to its greater rigidity. To reduce the cost, black totes used as water reservoir and planter are not fixed but just placed on the bottom platform, moving them along with the frame when the water level is high in addition to the weight of the planter is challenging. Mobility of the system is desired, but not strictly required, as maintenance of the systems can occur when transplanting and harvesting. Thus, the lowest cost systems would have no wheels, but would involve the most labor to use in a commercial growing facility. All systems presented here are suitable for crops with a large root system. Leafy green can also be planted; however, it is not desirable as the root systems of leafy greens do not require much volume to show the advantages of the bin systems with its capacity. Thus, the vertical grow walls in the agrivoltaics agrotunnel are preferred as there is much higher density of crops per unit floor area.

The irrigation frequency and duration are controlled by a programmable timer [104]. This technique can be scaled with a single timer that can control multiple water pumps by adding extension cords. With drainage holes present, users just need to ensure the duration of watering will saturate the growing medium, and the excessive water will drain out and collected by the reservoir below the planter. The limitation here is that different stages of the plant will require different amount or frequencies of irrigation, so users should physically inspect how fast the substrate dries out and adjust the frequency of the watering accordingly as the plants develop (or use a smart open-source irrigation system that can automate this process [105–107]). Since the programmable timer can only control one outlet, it means all pumps connected to the same timer will operate at the same time for the same duration. In this case, if users want to plant a variety of crops with different irrigation needs within the same frame, more programmable timers will be required accordingly. This study focuses on the design part of an indoor growing structure, but there are other variables for which these designs can be used to study such as different combinations of red and blue lights on the behavior of leaf photosynthesis [108–110], as well as the need for air circulation on plants' canopy [111].

Indoor growing normally takes place using stacked horizontal flats with horizontal lights or vertical grow walls with vertical lights [4]. A common problem associated with the horizontal method is micro-climate created by the heat dissipated from artificial grow light the accumulating at the top of each layer, which can heat up the plant canopy of the current layer as well as the layer above as the same structure is stacked up [56]. Those climate problems can be dealt with by implementing natural or forced ventilation strategies within the growing structure [112], but that comes with additional material and energy cost.

Indoor growing could be traced back to the 1800s [113], initially practiced by middle and upper class for leisure and hobby, slowly it is becoming an essential part of the urban produce supply [46,114]. Many products are also available online that allow consumers to grow crops at home [115–117], mostly for leafy green and other short-term crops. The systems presented here have a larger capacity to grow root vegetables such as potatoes and carrots as well as berry bushes. The structures detailed here could be improved. For example, if these are implemented at home with an ideal location to receive natural sunlight, the entire structure could be reduced to bins or containers to house the plants and nutrient solutions. The mobility of the structure is also not strictly required, and only needed for cleaning and reallocation. Removing the mobility features from the bin designs would give additional percentage savings of 11.2% for Inverted T, 6.8% Boxed Rectangle and 8.1% for the PVC frame system, respectively. These savings are an underestimation as they are realized by only removing the wheels, including the screws and nuts required. Realistic savings will be more by excluding the bottom platform completely as fewer aluminum extrusions are needed. Furthermore, vertical extrusions are just for the purpose of hanging grow light, whose cost can also be eliminated by attaching lights on the ceiling for example. In this study only a select set of berries are tested, even though they successfully flowered and produced fruits, other crops should also be tested. As the systems here are already in a controlled environment, the performance of the systems could differ significantly depending on the deployment location. Ideally with autonomous watering no care will be required, however, manual pollination was required with berries bushes. Studies also show that temperature variance could affect the yield and growth of certain crops [118,119], which is not included in this study since the facility uses continuous lighting and a constant temperature of 21°C is maintained. Future studies can target how to reduce the cost more while maintaining the functionality of the system. While prototyping these designs, to the costs were minimized by using economical materials such as 2020 aluminum extrusions and ½" PVC pipes. Although they do provide the necessary functionalities to support the growing light and the bins, an upgrade of materials and structural integrity could be implemented. Improvements could be made to the secondary features such as maneuverability and overall integrity by using more aluminum extrusions and better-quality industrial castor wheels.

## 5. Conclusions

The indoor growing designs shown here provide the necessary structure for supporting the grow light and the grow bins. They provide a comparable amount of grow volume from a maximum of 106 to 192 L, while the commercial product has a maximum grow volume of up to 110 L. Similarly of the water reservoir volume, commercial product has a tank of 62 L, while the open-source systems' water reservoir ranges from 64 to 192 L. Commercial product gives a growing area of 0.5 m<sup>3</sup>, the open-source systems' growing areas range from 0.51 to 0.76 m<sup>3</sup>. Mostly importantly, the percent savings of cost per growing surface area are all above 90% compared to the commercial product, and more could be realized by using 3D printing technology, removing the bottom platform, or supporting the grow light by other means such as suspending it from the ceiling. The structures enabled the transplanted berry plants to flower and produced fruits. Some limitations (no organic materials, restrictions on adhering mechanical components to the walls and ceilings) raised here are from the strict biological protocols and physical conditions of the agrotunnel facility used to test these structures. Future work plans on improving the current structures, testing other types of crops as potatoes and carrots targeting remote communities where such food sources are imported. Furthermore, the performance of these structures can be determined for the yield per container to compare with the conventional growing methods.

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## Appendix A

The full BOMs are shown in Table A1 for Inverted T structure, Table A2 for Boxed Rectangle structure, Table A3 for Single Water Reservoir structure, and Table A4 for PVC frame.

Table A1. BOM for Inverted T structure.

Components	Function	Quantity	Price (CAD)	URL
2020 Aluminum Extrusion	Frame	32	\$119.03	<a href="https://www.amazon.ca/Aluminum-Extrusion-European-Standard-Anodized/dp/B09SF492NK">https://www.amazon.ca/Aluminum-Extrusion-European-Standard-Anodized/dp/B09SF492NK</a>
T Shape Joint Plates (Can be 3D printed)	Connection	4	\$17.33	<a href="https://www.amazon.ca/Plates-T-Slot-Aluminum-Profile-Accessories/dp/B0B9JYV7NP">https://www.amazon.ca/Plates-T-Slot-Aluminum-Profile-Accessories/dp/B0B9JYV7NP</a>
M5 Drop in Tee Nut	Connection	78	\$21.82	<a href="https://www.amazon.ca/Boeray-Carbon-Hammer-Aluminum-Extrusion/dp/B01G7ZYHHI">https://www.amazon.ca/Boeray-Carbon-Hammer-Aluminum-Extrusion/dp/B01G7ZYHHI</a>
M5 0.8 * 8 mm Screws	Connection	78	\$23.04	<a href="https://www.amazon.ca/M5-0-8-Button-Stainless-Machine-Threaded/dp/B0B7DSMN2N">https://www.amazon.ca/M5-0-8-Button-Stainless-Machine-Threaded/dp/B0B7DSMN2N</a>
Corner Bracket (Can be 3D printed)	Connection	14	\$7.20	<a href="https://www.amazon.ca/Bracket-Aluminum-Extrusions-Fastener-Printer/dp/B085NRPPNM">https://www.amazon.ca/Bracket-Aluminum-Extrusions-Fastener-Printer/dp/B085NRPPNM</a>
Caster Wheels	Mobility	6	\$19.49	<a href="https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740">https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740</a>
Grow Light Rope Hanger	Light Support	2	\$5.50	<a href="https://www.amazon.ca/VIPARSPECTRA-Adjustable-Fixtures-Gardening-Capacity/dp/B07Z613ZM2/">https://www.amazon.ca/VIPARSPECTRA-Adjustable-Fixtures-Gardening-Capacity/dp/B07Z613ZM2/</a>
Total Price:			\$213.41	
3D printed Corner Brackets (7.22 g PETG)		14	\$3.03	

Total Price with 3DP Replacement:	\$209.24	1.95% savings
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Table A2. BOM for Boxed Rectangle structure.

Components	Function	Quantity	Price (CAD)	URL
2020 Aluminum Extrusion	Frame	68ft	\$252.94	<a href="https://www.amazon.ca/Aluminum-Extrusion-European-Standard-Anodized/dp/B09SF492NK">https://www.amazon.ca/Aluminum-Extrusion-European-Standard-Anodized/dp/B09SF492NK</a>
Corner Bracket (Can be 3D printed)	Connection	36	\$18.51	<a href="https://www.amazon.ca/Aluminum-Profile-Connector-Bracket-Accessories/dp/B0B9JWV5X8">https://www.amazon.ca/Aluminum-Profile-Connector-Bracket-Accessories/dp/B0B9JWV5X8</a>
M5 0.8 * 8 mm Screws	Connection	92	\$27.18	<a href="https://www.amazon.ca/M5-0-8-Button-Stainless-Machine-Threaded/dp/B0B7DSMN2N">https://www.amazon.ca/M5-0-8-Button-Stainless-Machine-Threaded/dp/B0B7DSMN2N</a>
Grow Light Rope Hanger	Light Support	2	\$5.50	<a href="https://www.amazon.ca/VIPARSPECTRA-Adjustable-Fixtures-Gardening-Capacity/dp/B07Z613ZM2">https://www.amazon.ca/VIPARSPECTRA-Adjustable-Fixtures-Gardening-Capacity/dp/B07Z613ZM2</a>
M5 Drop in Tee Nut	Connection	92	\$25.74	<a href="https://www.amazon.ca/Boeray-Carbon-Hammer-Aluminum-Extrusion/dp/B01G7ZYHHI">https://www.amazon.ca/Boeray-Carbon-Hammer-Aluminum-Extrusion/dp/B01G7ZYHHI</a>
Caster Wheels	Mobility	6	\$19.49	<a href="https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740">https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740</a>
Total Price:			\$349.35	
3D printed Corner Brackets (7.22 g PETG)		36	\$7.80	
Total Price with 3DP Replacement:			\$338.64	3.07% savings

Table A3. BOM for Single Water Reservoir System.

Components	Function	Quantity	Price (CAD)	URL
Profile 4040 Aluminum Extrusion	Frame	27ft	\$337.50	<a href="https://www.amazon.ca/Aluminum-Extrusion-European-Standard-Anodized/dp/B09MWDQVB3">https://www.amazon.ca/Aluminum-Extrusion-European-Standard-Anodized/dp/B09MWDQVB3</a>
10 pk 1/4-20 Slide-In Centered T-	Connection	3 pack	\$29.97	<a href="https://www.princessauto.com/en/10s-10-pk-1-4-20-slide-in-centred-t-nut-fbhscs-bolt-">https://www.princessauto.com/en/10s-10-pk-1-4-20-slide-in-centred-t-nut-fbhscs-bolt-</a>

Nut				<a href="https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740">assembly/product/PA0009132473</a>
Caster Wheels	Mobility	6	\$11.99	<a href="https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740">https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740</a>
Total Price:			\$379.46	

Table A4. BOM for PVC frame.

Components	Function	Quantity	Price (CAD)	URL
1/2" PVC Pipe	Frame	43.5ft	\$137.68	<a href="https://www.amazon.ca/letsFix-Schedule-Furniture-Plumbing-Available/dp/B08KGZBGV5">https://www.amazon.ca/letsFix-Schedule-Furniture-Plumbing-Available/dp/B08KGZBGV5</a>
2020 Aluminum Extrusion	Frame	25ft	\$93.00	<a href="https://www.amazon.ca/Aluminum-Extrusion-European-Standard-Anodized/dp/B09SF492NK">https://www.amazon.ca/Aluminum-Extrusion-European-Standard-Anodized/dp/B09SF492NK</a>
Caster Wheels	Mobility	6	\$19.49	<a href="https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740">https://www.princessauto.com/en/4-pk-2-in-light-duty-swivel-casters/product/PA0008937740</a>
3 Way 1/2" Tee PVC (Can be 3D printed)	Connection	8	\$18.32	<a href="https://www.amazon.ca/Fittings-Connector-Furniture-Structure-Connection/dp/B0BQWJKY2Z">https://www.amazon.ca/Fittings-Connector-Furniture-Structure-Connection/dp/B0BQWJKY2Z</a>
3 way 1/2" PVC Connector(Can be 3D printed)	Connection	6	\$11.40	<a href="https://www.amazon.ca/Yuema-Fitting-Build-Furniture-Fittings/dp/B082NRMNLK">https://www.amazon.ca/Yuema-Fitting-Build-Furniture-Fittings/dp/B082NRMNLK</a>
Corner Bracket (Can be 3D printed)	Connection	16	\$8.16	<a href="https://www.amazon.ca/Bracket-Aluminum-Extrusions-Fastener-Printer/dp/B085NRPPNM">https://www.amazon.ca/Bracket-Aluminum-Extrusions-Fastener-Printer/dp/B085NRPPNM</a>
1/2" 45 Degree 2 Way Tee PVC (Can be 3D printed)	Connection	4	\$5.60	<a href="https://www.amazon.ca/QWORK-Fitting-Furniture-Building-Structures/dp/B09DYHHTMY">https://www.amazon.ca/QWORK-Fitting-Furniture-Building-Structures/dp/B09DYHHTMY</a>
Total Price:			\$293.64	
3D printed 3 Way 1/2" Tee PVC (35.58g)		8	\$8.54	
3D printed 3- Way PVC Connector (37.45g)		6	\$6.74	
3D printed Corner Brackets (7.22		16	\$3.47	

g PETG)		
3D printed		
1/2" 45 Degree	4	\$2.20
2-way Elbow (18.37g)		
Total Price		
with 3DP	\$250.16	14.80% savings
Replacement:		

Table A5. Universal components for a single bin system.

Components	Quantity	Price (CAD)	URL
64L Stackable Tote Bin	2	\$23.94	<a href="https://www.homedepot.ca/product/hdx-64l-stackable-tough-strong-storage-tote-bin-plastic-organizer-box-black-base-yellow-snap-on-lid/1001057029">https://www.homedepot.ca/product/hdx-64l-stackable-tough-strong-storage-tote-bin-plastic-organizer-box-black-base-yellow-snap-on-lid/1001057029</a>
Rule Bilge Water Pump 750 GPH 12V	1	\$23.66	<a href="https://www.amazon.ca/Iztor-Bilge-Water-Marine-outlet/dp/B078GN8BNV">https://www.amazon.ca/Iztor-Bilge-Water-Marine-outlet/dp/B078GN8BNV</a>
12V 5A Power Supply Adapter	1	\$17.99	<a href="https://www.amazon.ca/dp/B01GEA8POA">https://www.amazon.ca/dp/B01GEA8POA</a>
RAIN BIRD 6-Port Drip Manifold	1	\$5.86	<a href="https://www.homedepot.ca/product/rain-bird-6-port-drip-manifold/1000836763">https://www.homedepot.ca/product/rain-bird-6-port-drip-manifold/1000836763</a>
3/4" PVC Tubing	4 ft	\$4.90	<a href="https://www.amazon.ca/Duda-Energy-HPpvc075-025ft-Pressure-Resistant/dp/B00TMTFV3G">https://www.amazon.ca/Duda-Energy-HPpvc075-025ft-Pressure-Resistant/dp/B00TMTFV3G</a>
1/2" x 1" Close PVC Riser	1	\$3.87	<a href="https://www.homedepot.ca/product/rain-bird-1-2-x-1-close-pvc-riser/1001493451">https://www.homedepot.ca/product/rain-bird-1-2-x-1-close-pvc-riser/1001493451</a>
Reducing Elbow - 3/4" Insert X 1/2"	1	\$2.72	<a href="https://www.homedepot.ca/product/pro-connect-pvc-female-combination-reducing-elbow-3-4-inch-insert-x-1-2-inch-fpt/1000123309">https://www.homedepot.ca/product/pro-connect-pvc-female-combination-reducing-elbow-3-4-inch-insert-x-1-2-inch-fpt/1000123309</a>
1/2-inch Mt x Ft Swing-joint Elbow	1	\$1.84	<a href="https://www.homedepot.ca/product/orbit-watermaster-1-2-inch-mt-x-ft-swing-joint-elbow-dbx/1000117543">https://www.homedepot.ca/product/orbit-watermaster-1-2-inch-mt-x-ft-swing-joint-elbow-dbx/1000117543</a>
Total Price:		\$84.78	

Table A6. Extra material for Single water reservoir system.

Components	Quantity	Price (CAD)	URL
Small Stackable Tote	6	\$41.94	<a href="https://www.princessauto.com/en/product/PA0008197469">https://www.princessauto.com/en/product/PA0008197469</a>
25' x 3/4" ID PVC Tubing	1	\$30.62	<a href="https://www.amazon.ca/Duda-Energy-HPpvc075-025ft-Pressure-Resistant/dp/B00TMTFV3G">https://www.amazon.ca/Duda-Energy-HPpvc075-025ft-Pressure-Resistant/dp/B00TMTFV3G</a>
Rule Bilge Water Pump	1	\$23.66	<a href="https://www.amazon.ca/Iztor-Bilge-Water-Marine-outlet/dp/B078GN8BNV">https://www.amazon.ca/Iztor-Bilge-Water-Marine-outlet/dp/B078GN8BNV</a>

750 GPH 12V			
64L Stackable Tote Bin	1	\$10.97	<a href="https://www.homedepot.ca/product/hdx-64l-stackable-tough-strong-storage-tote-bin-plastic-organizer-box-black-base-yellow-snap-on-lid/1001057029">https://www.homedepot.ca/product/hdx-64l-stackable-tough-strong-storage-tote-bin-plastic-organizer-box-black-base-yellow-snap-on-lid/1001057029</a>
Rain gutter cover	1	\$9.59	<a href="https://www.amazon.ca/OSALADI-Attachment-Downspout-K-style-Accessories/dp/B0C7FMW59F">https://www.amazon.ca/OSALADI-Attachment-Downspout-K-style-Accessories/dp/B0C7FMW59F</a>
rain gutter	1	\$8.19	<a href="https://www.rona.ca/en/product/euramax-contemporary-half-round-gutter-white-vinyl-120-in-l-x-4-in-w-t0473-0128056">https://www.rona.ca/en/product/euramax-contemporary-half-round-gutter-white-vinyl-120-in-l-x-4-in-w-t0473-0128056</a>
PVC pipe 3/4"	1	\$5.48	<a href="https://www.homedepot.ca/product/sharkbite-3-4-inch-x-5-feet-white-pe-x-pipe/1001013602">https://www.homedepot.ca/product/sharkbite-3-4-inch-x-5-feet-white-pe-x-pipe/1001013602</a>
Total Price:			\$130.45

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