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Home gardening in Singapore: A feasibility study of vertical gardening for self-sufficiency in high-rise public housing apartment buildings

Shuang Song[a,*], Jia Chin Cheong[a], Joel S.H. Lee[a], Jonathan K.N. Tan[a], Zhongyu Chiam[a], Srishti Arora[a], Karl J.Q. Png[a], Johanah W.C. Seow[a], Felicia W.S. Leong[a], Ankit Palliwal[b], Filip Biljecki[c,d], Abel Tablada[c,e], Hugh T.W. Tan[a]

[a] Department of Biological Sciences, Faculty of Science, National University of Singapore, 16 Science Drive 4, 117558, Singapore

[b] Department of Geography, Faculty of Arts & Social Sciences, National University of Singapore, 1 Arts Link, 117570, Singapore

[c] Department of Architecture, School of Design and Environment, National University of Singapore, 4 Architecture Drive, 117566, Singapore

[d] Department of Real Estate, School of Design and Environment, National University of Singapore, 4 Architecture Drive, 117566, Singapore

[e] Faculty of Architecture, Technological University of Havana J. A. Echeverría, Edificio 6, Marianao 11920, Cuba

[*]Corresponding author: Shuang Song; e0223230@u.nus.edu; Department of Biological Sciences, National University of Singapore, 16 Science Drive 4, 117558, Singapore

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ABSTRACT

In land-scarce cities, high-rise apartment buildings may provide vertical spaces for natural-light home gardening along corridors, rooftops, balconies as well as façades. The vertical space can improve not only urban environmental sustainability but also food security. Using an experimental approach, we investigated the food production potential of a high-rise public housing apartment building based on different gardening systems, food crop, and sunlight availability. A gardening prototype system for building corridors was shown to increase the unit area yield of corridor gardening by fivefold compared to a commercial trough planter system. Additionally, this commercial trough planter system was mainly for leafy vegetable production, whereas the gardening prototype system for corridors is also suitable for climbing crops, such as legumes and cucurbits. Nevertheless, because of the limited space along corridors of the apartment building and the relatively low-light levels on average, corridor gardening was estimated to meet only 0.5% of the demand for vegetables of the residents living in the apartment building. Shallow-growing medium, rooftop gardening (depth < 15 cm) was estimated to meet 3% of demand, and façade gardening 43%, given the larger space available. Although the vegetable production potential in this study was estimated based on a particular typology of public housing apartment buildings in Singapore, our results showed that vegetable production in public housing apartment buildings is feasible, and home gardening can produce a substantial amount of vegetables for consumption if well deployed. Governments of highly urbanized cities may wish to invest in better home garden designs for high-rise public housing apartment buildings and encourage residents' participation in home gardening, which would increase high-rise greenery coverage and improve urban food system resilience. Future studies should also investigate the environmental sustainability and food safety aspects of home gardening in highly urbanized cities.

KEY WORDS

Façade gardening; corridor gardening; extensive green roof; urban farming; food security

1. INTRODUCTION

The current COVID-19 pandemic has highlighted the vulnerability of global food systems to disruptions (Siche, 2020), in particular, through the disrupted supply chain, loss of purchasing power, and the fluctuation of food prices (Clapp & Moseley, 2020). Cities are particularly vulnerable to food supply chain disruptions as they import most of their food, and there is a need to improve their food system resilience (Hecht et al., 2019). Increasing local production is an important strategy to improve local food system resilience (Blay-Palmer et al., 2021; Langemeyer et al., 2021). Other than increasing commercial farm production, urban subsistence or home gardening has been shown to reduce the vulnerability of food-insecure households to the fluctuation of food price (Baiphethi & Jacobs, 2009). However, most of the home gardens mentioned in the literature are backyard gardens, with plants directly cultivated in the ground or raised beds near the gardeners' homes, such as in Cape Town (Engel et al., 2019), Madison (Smith et al., 2013), Oman (Al-Mayahi et al., 2019), and Vancouver (Patel et al., 2011), and sometimes these home gardens can become commercialized when the production level is sufficiently high (Bellwood-Howard et al., 2018). Nonetheless, for highly urbanized and densely populated cities, such as Singapore and Hong Kong, using prime city land for agriculture would have the opportunity cost of using the same land for commercial, residential or industrial purposes (Clapp & Moseley, 2020). Instead, the underutilized vertical space of apartment buildings, such as balcony or corridor space, façades, and rooftops can be used for home gardening.

Utilizing the vertical space of buildings for greenery is already a common practice in cities. Vertical greenery has been extensively studied for its environmental services (Ghazalli et al., 2019; Rupasinghe & Halwatura, 2020). A green façade improves thermal performance and building energy savings (Wong et al., 2010; Coma et al., 2017). Suitability of plant species for vertical façades has been studied (Abd Ghafar et al., 2020), but most of the species examined were ornamental (Chernova et al., 2020). Vertical greenery along building corridors has been shown to stabilize the humidity level and reduce the particulate matter levels (Ghazalli et al., 2018). The thermal performance of vertical greenery using the edible winged bean species, *Psophocarpus tetragonolobus*, in a residential balcony, has also been studied, but not its yield (Basher, 2019).

Green roofs have been shown to store rainwater, reduce the urban heat island effect, and improve air quality and the quality of life (Shafique et al., 2018). Here, green roofs refer to vegetated roofs in general so refer to both extensive and intensive green roofs. Compared to other vertical home gardens, the potential of green roofs for food production is relatively well studied. Intensive soilless farming on rooftops was estimated to produce sufficient food to meet the demand of 77% of the residents' needs (Orsini et al., 2014). The productivity of rooftop hydroponics systems can be as high as 19.53 kg m^{-2} yr^{-1} (Grewal & Grewal, 2012), while that of a soil-based green roof was lower at 7.23 kg m^{-2} of vegetables a year (Peck, 2003). Models to predict light levels on roofs and yields of rooftop greenhouses and rooftop vertical farms, as well as to select vertical gardening designs were also developed (Benis et al., 2017; Ivanova et al., 2020a; Wu & Biljecki, 2021). Leafy vegetables can grow reasonably well in shallow extensive green roof systems (< 15 cm growing-medium depth) when there is sufficient water and nutrients (Walters & Stoelzle Midden, 2018), and growing leafy vegetables on rooftops, such as lettuce, would also have smaller environmental impacts than growing fruiting vegetables, such as tomato (Dorr et al., 2017). However, almost 50% of the studies on urban rooftop gardening were conducted in North America (Appolloni et al., 2021), and the potential of the vertical spaces of buildings for food production has not been systematically studied.

This study aimed to estimate the fresh vegetable production potential in vertical home gardens in public housing apartment buildings, especially leafy vegetables and herbs which are highly perishable and are more suitable for local production to reduce the length of the supply chain. Singapore was selected as the case study, as many residents of the public housing apartment buildings practice gardening at home (Kosorić et al., 2019). A plant survey across the corridors of 1.86 ha of public housing apartment buildings in Singapore identified 265 species (Oh et al., 2018). A door-to-door survey of residents staying in public housing apartment buildings also showed that > 50% of the respondents grow vegetables and herbs at home in Singapore, and the most preferred locations of gardens are corridors and windows (37.3%) followed by rooftops (26.3%), according to Kosorić et al. (2019) (n = 391). However, growing edibles on high-rise buildings has its own challenges. Owing to the closeness of apartment buildings, certain façades or certain levels of the building may not receive adequate sunlight to grow vegetables, which would directly affect the photosynthesis rate and yield (Song et al., 2018). Given there are approximately 10,000 existing public housing apartment buildings in Singapore (Housing & Development Board, 2022), this study evaluated the feasibility of improving the food production in these existing buildings by using various home gardening prototypes for corridor gardening, roof gardening as well as façade gardening. Although green residential buildings or green-living towers may be more productive, they are excluded in this study because they would require substantial structural alteration of buildings, which may be more suitable to be integrated in the design stage of new public housing apartment development projects. In the current study, the main consideration was the building floor loading limit, and the prototypes selected were generally lightweight systems using shallow substrates (< 10 cm in depth) rather than the more commonly used deeper substrate for intensive gardening (Cascone et al., 2018; Walters &

Stoelzle Midden, 2018). Through an experimental approach, we estimated the vegetable production potential of a public housing apartment building's corridors, façades and rooftop, taking into consideration the light availability, as we expected that it would affect the productivity of the vertical gardening systems. The theoretical self-sufficiency level achievable with home gardening in terms of vegetable requirement was also calculated. The results of this study may provide urban planners and policy makers with some insights on the feasibility of using vertical home gardens as a supplementary food source in cities.

2. MATERIALS & METHODS

Multiple growth experiments were conducted to estimate the potential productivity home gardeners can achieve when utilizing building corridors, rooftops and façades for gardening.

2.1. Growth experiments for building corridor gardening prototypes

To maximize the use of space along building corridors, a multi-tiered vertical corridor gardening prototype was developed to grow leafy vegetables and climbing crops simultaneously (Fig. 1A). The prototype was modified from a 43-cm (length) × 33-cm (width) × 107-cm (height) Toyogo® cabinet (Model 802-5). The top four drawers in the five-tier cabinet were modified into planter troughs. The bottom drawer was designed for composting but was not tested in this growth experiment. A wooden support frame was used to envelope the whole cabinet with an adjustable trellis to provide space for climbing vines as the lower drawers are likely to be shaded by the corridor's parapets in a real-life public housing apartment building corridor setting, as some corridors have railings that allow light to pass through whereas the other corridors have parapet walls (Fig. 1B; Supplementary Material: Fig. S1.1). A lightweight soilless growing medium consisting of cocopeat (powdered coconut fruit husk), commercial compost, and perlite was used for cultivating the vegetables. For the oyster mushroom cultivation, the growing medium was spent coffee grounds. Five sets of the multi-tiered prototype were used to grow different combinations of selected fast-growing leafy vegetables, fruiting vegetables, sprouts and oyster mushrooms (Table 1) with vegetable seeds and cuttings as well as mushroom spawn sourced locally. Non-climbing leafy vegetables, including Chinese spinach (*Amaranthus tricolor*), choy sum (*Brassica rapa* Cultivar Group Caisin) and water spinach (*Ipomoea aquatica*), were cultivated in the top tier. Vegetable vines were grown on the next three tiers with the exception of one setup where pea sprouts (*Pisum sativum*) and oyster mushroom (*Pleurotus ostreatus*) were cultivated in the third and fourth tier from the top, respectively. All five setups were placed along a corridor located at level 3 of Block S3 of the National University of Singapore (NUS) Kent Ridge Campus (1.295588N, 103.778647E). The growth experiment for individual setups was terminated when all crops in a setup had passed their peak production phases or on the 90th day, whichever came earlier.

To gauge the performance of the multi-tiered prototype, a commercially available hanging trough planter system (48.9-cm (length) × 18.7-cm (width) × 15.6-cm (height); BABA®, model BI-509 Planter Box, Malaysia) was placed at five public housing apartment buildings in different estates of Singapore (Fig. 1B). At each location, eight sets of the hanging trough planters were established and maintained by one volunteer to grow a single type of leafy vegetable of their choice. A list of guidelines on watering and fertilizer application was also provided to them (Supplementary Material, S1.2), but depending on the vegetable choice and the specific environmental conditions of the experimental site, the volunteers were allowed to modify their gardening practices based on their own judgement. The growth experiment at each site was terminated when the leafy vegetable grown at the site has passed their peak production phases or on the 60th day, whichever came earlier.

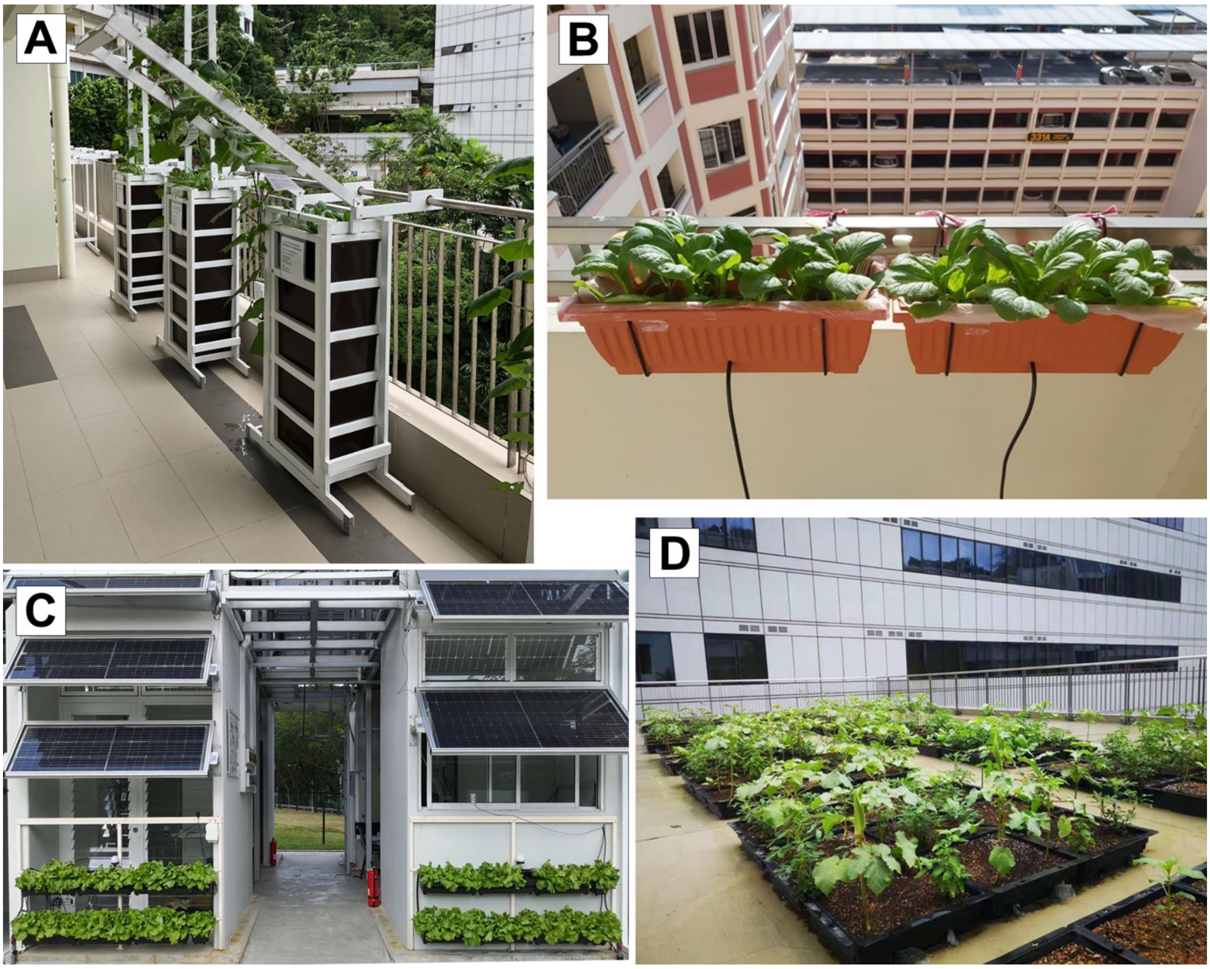

Fig. 1. Vertical gardening systems used to quantify potential vegetable production in a public housing apartment building. A) Three vertical multi-tiered gardening prototypes with adjustable trellis placed along a building corridor. The trellis can be lowered from the vertical position for convenient and safe maintenance. B) Typical hanging troughs used for home gardening in Singapore placed along a residential apartment corridor (photo credit: Tan Wei Quan Joel). C) Façade planter system prototypes installed at the NUS-CDL Tropical Technologies Laboratory, an experimental house-like structure. The façade on the left is the balcony façade while the one on the right is the wall façade. D) An extensive green roof (depth < 15 cm) gardening system placed on a building rooftop.

Table 1. List of crop species selected for the multi-tiered vertical corridor gardening prototypes.

Vernacular Name	Botanical Name	Source	Typical Growth Period
Chinese spinach	*Amaranthus tricolor*	Seed	25–28 days
Bitter gourd	*Momordica charantia*	Seed	60 days
Choy sum	*Brassica rapa* Cultivar Group Caisin	Seed	28–30 days
Cucumber	*Cucumis sativus*	Seed	35 days
French bean	*Phaseolus vulgaris*	Seed	45 days
Water spinach	*Ipomoea aquatica*	Seed	20–25 days
Long bean	*Vigna unguiculata*	Seed	55 days

Vernacular Name	Botanical Name	Source	Typical Growth Period
Malabar spinach (green)	*Basella alba* (green-leafed cultivar)	Cutting	50 days
Malabar spinach (red)	*Basella alba* (red-leafed cultivar)	Cutting	50 days
Pumpkin	*Cucurbita moschata*	Seed	110 days
Sweet potato vine (green)	*Ipomoea batatas* (green-stemmed cultivar)	Cutting	30 days
Sweet potato vine (purple)	*Ipomoea batatas* (purple-stemmed cultivar)	Cutting	30 days
Winged bean	*Psophocarus tetragonolobus*	Seed	60–70 days
Snow pea sprout	*Pisum sativum* var. *saccharatum*	Seed	7 days
Oyster mushroom	*Pleurotus ostreatus*	Spawn	10–14 days

For all setups, ratoon harvesting was done for leafy vegetables when they were approximately market size or had overgrown their troughs. For fruiting vegetables, fruits of approximately market size were harvested when available. During each harvest, the total fresh weight from each setup was recorded. The amount of sunlight at each of the experimental site was also monitored continuously throughout the experimental period using a photosynthetic active radiation (PAR) sensor connected to a data logger (Onset Computer Corporation, Massachusetts, USA), and the aggregate PAR readings at each site were then converted to the daily light integral (DLI) to compare the amount of sunlight at the different sites according to Song et al. (2018).

2.2. Growth experiments for rooftop gardening

To estimate the potential yield of rooftop gardening, we used the prefabricated extensive green (PEG) roof tray system (Fig. 1D; 50-cm (length) × 50-cm (width), Housing & Development Board, Singapore and Eng Seng Tech Pte Ltd, Singapore) designed for shallow growing medium on rooftops (maximum weight with saturated soil = 120 kg m^{-2}; medium depth < 15 cm), as most of the existing public housing apartment buildings' roofs in

Singapore are not designed for heavy loading. A soil-based substrate was used for the PEG roof tray system as it is the most common and preferred method for urban rooftop gardening (Thomaier et al., 2015; Specht et al., 2016; Appolloni et al., 2021). Trial experiments were conducted to test the watering regimes, suitable species and planting density (data not shown). For the actual growth experiment, four vegetable species were selected because of their different nutritional values and culinary uses, namely basil (*Ocimum basilicum*), mustard (*Brassica juncea*), okra (*Abelmoschus esculentus*) and peanut (*Arachis hypogaea*). In each tray, either four individuals of the same species (monoculture) or four individuals of all different species (polyculture) were planted to determine which treatment would produce a higher yield, as it has been shown that polyculture would improve the fresh weight of the individual plants while reducing the amounts of fertilizer and pesticide used (Landis et al., 2000; Liebman, 2018). The arrangement of the monoculture and the polyculture trays were randomized, and there were nine trays of monoculture treatment for each species and 36 trays of polyculture treatments in total. The growth experiment was run over 42 days (excluding 28 days in the nursery before transplanting). More details of the gardening practices can be found in the Supplementary Materials S2.

2.3. Growth experiments for the vertical façade gardening prototypes

The feasibility of using building's vertical façades for food production was tested using a vertical prototype installed at the NUS-CDL Tropical Technologies Laboratory, an experimental building (1.203279N, 103.769802E) designed by Tablada et al. (2018) and named as productive façades which were to integrate photovoltaic panels and farming systems into building façades. This building consisted of four sides, each of which faces north, east, south and west, respectively. For each side, there are two façades—a balcony façade and wall façade (Fig. 1C). Although most of the façades are wall façades in

Singapore, most apartment buildings would also include a balcony for each household (Supplementary Material: Fig. S3.1). For each façade, two rows of planters (50-cm (length) × 15-cm (width) × 17-cm (height); PlanterCell® model 170, Uniseal, Singapore) were mounted to the railing and each row had three planters. The lightweight soilless growing medium consisting of cocopeat, commercial compost and perlite was used again. Prior to the actual growth experiment, a preliminary experiment was conducted to compare the suitability of Chinese spinach, pak choy (*Brassica rapa* Cultivar Group Pak Choi Green-Petioled Form), water spinach and lettuce (*Lactuca sativa*) for the green façade, and lettuce was selected for the experiment as it had better overall performance than the others (results not shown). Three lettuce seedlings were transplanted to each planter after 14 days in the nursery. The growth experiment for lettuce was conducted over five growth cycles each of which lasting 45 days with the fresh weight of individual lettuce plants measured at the end of each growth cycle. The DLI was measured following the method under Section 2.1. More details of the façade growth experiment can be found in Supplementary Material S3.

2.4. Calculation of theoretical vegetable production of a public housing apartment building

To calculate the potential vegetable yield of a public housing apartment building, Block 633 of Jurong West Street 65 (1.343250N, 103.700619E) was selected as the model building, as the light levels (DLI) received by its façades had been estimated by Palliwal et al. (2021) using 3D building models. Block 633 is a 16-storey public housing apartment building (Housing & Development Board, 2021). It is close to Block 632 (Fig. 2A) and its façades can be generalized into three corridor façades (corridors A to C; Fig. 2B) and six wall façades (F1 to F6; Fig. 2B). All six wall façades have windows installed, similar to the wall façade in Fig. 1C. The simulated light level for each floor of the building from Palliwal et al. (2021) was used to estimate the potential yield of corridor and façade gardening in this study. The lengths of the corridor and the wall façades, the rooftop space, and the building area were estimated using Google Earth Pro 7.3 (Google, n.d.). Owing to the presence of water tanks on the rooftop, the area with the water tanks was excluded from the usable space on the rooftop for gardening. Additionally, it was assumed that 30% of the remaining space on the rooftop would be used for paths and storage of fertilizers, substrates and gardening tools rather than for vegetable production. The length of corridor A was estimated to be 8 m, corridor B was 31 m and corridor C was 4 m per storey. The total usable length of the façades (including windowless sections) was estimated to be 136 m per storey, the total usable rooftop area was estimated to be 392 m^2 after 30% reduction, and the building area was estimated to be 1320 m^2. It was assumed the windowless part of the façades could theoretically be accessed through external scaffolds by the residents as demonstrated in the testbed vertical garden at Tampines Block 146 (Zheng, 2022) and therefore available for vegetable production.

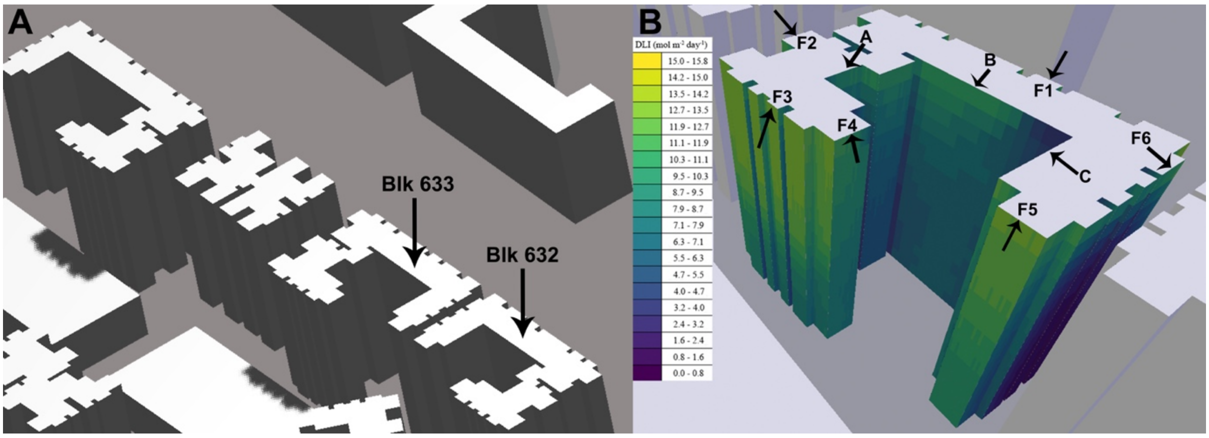

Fig. 2. A) 3D models of Block 633, Jurong West Street 65, Singapore and its surroundings. B) The corridor and wall façades of Block 633 and the simulated light levels (Palliwal et al., 2021).

A few assumptions were made in the relationship between the DLI and the potential production level of the building corridors and façades. It was assumed that 1) at the rooftop where the DLI would be high (> 16 mol m^{-2} d^{-1} for leafy vegetable (Kohler & Lopez, 2021)), lighting would not be a limiting factor, as the photosynthetic light responses of plants to the DLI are generally concave functions (Geoffrey & Marc, 2019; Paz et al., 2019). Therefore, the yield obtained from the rooftop experiment was directly used as a potential yield of the edible green roof on public housing apartment buildings. For the building façade and corridors, where lighting may be limited, it was assumed that 2) the yield would increase proportionally with light availability (Fisher & Runkle, 2004; Paz et al., 2019). It was also assumed that 3) when the DLI falls below 6 mol m^{-2} d^{-1} crop growth would be slow, although depending on the species. A study using five culinary herbs showed that the plants could grow when the DLI was as low as 2.8 mol m^{-2} d^{-1}, but had low shoot dry mass accumulation when the DLI was < 6 mol m^{-2} d^{-1}. Paz et al. (2019) found that lettuce would require a minimal DLI of 6.5–9.7 mol m^{-2} d^{-1} for adequate yield and quality. Therefore, because of Block 633's closeness to Block 632, façade F6 receives very low levels of sunlight (Fig. 2B) and was considered unsuitable for vegetable production. For the other façades, the floors at which the DLI fell below 6 mol m^{-2} d^{-1} were excluded from the calculations.

To estimate the potential annual yield of the corridor gardening prototype across the floors of the building, we calculated the average weight of harvest per setup per growth cycle standardized based on DLI. Similarly, the standardized weight of harvest was also calculated for the commercial trough planter system tested along corridors, as well as the façade planter system. The potential annual yield was then estimated following Equation (1).

$$Y_{corr} = \sum_{i=1}^{16} W_{std} \times DLI_i \times N \quad (1)$$

Where Y_{corr} is the potential annual yield of a corridor façade of Block 633, W_{std} is the average weight of harvest per setup per growth cycle per DLI, DLI_i is the simulated DLI value for the corridor façade at level i, and N is the number of setups that can fit into the corridor at each level.

The potential achievable vegetable self-sufficiency level of the building was also calculated by considering the demand for vegetables of all the residents of the building. Block 633 has 138 household units, including 48 units of four-room flats and 90 units of five-room flats (Housing & Development Board, 2021). The average household size for four-room flats and five-room flats is 3.29 and 3.67 persons, respectively (Department of Statistics Singapore, 2021). The number of residents living in Block 633 was, therefore, estimated to be 488 persons. The per capita vegetable consumption of Singapore residents is 95 kg per year (Singapore Food Agency, 2020), so the annual vegetable consumption of the residents of Block 633 was estimated to be 46,360 kg. The self-sufficiency rate by percentage was then calculated as the ratio between annual vegetable production of the building and the annual vegetable consumption of the building as shown in Equation (2). Nonetheless, this self-sufficiency rate only considered the quantity of vegetables produced and consumed, without accounting for the nutritional values and the diversity required by the population.

$$\%\, self\text{-}sufficiency\, rate = \frac{Theoretical\ vegetable\ production}{Theoretical\ vegetable\ consumption} \times 100 \quad (2)$$

2.5. Statistical analyses

To understand how the use of monoculture and polyculture treatments may potentially affect the shoot fresh weight of basil, mustard, okra, and peanut in the rooftop experiment, the shoot fresh weight of individual plant was used as the response variable with plant species, diversity treatment (monoculture vs polyculture), and their interaction terms being the explanatory variable in the full model. Model reduction was done followed by pairwise comparison of the effects of the monoculture and polyculture treatments within each species. For the façade experiment, the shoot fresh weight of the individual lettuce plant was used as the response variable whereas experimental round, direction of the façade and the presence of the balcony, as well as all the two-way interactions were included in the full model as the explanatory variables. The shoot-fresh-weight data were log- or square-root-transformed when necessary to meet the assumption of normal distribution. The statistical analyses and graphical visualizations were done in the R statistical computing environment v4.0.4 (R Core Team, 2021), through the RStudio integrated development environment v1.4.1106 (RStudio Team, 2021).

3. RESULTS

To estimate the potential vegetable production level home gardeners can achieve in public housing apartment buildings, an experimental approach was used to obtain yield data from corridor, rooftop and façade gardening.

3.1. Experimental vegetable production from the different gardening practices

The gardening prototype system for building corridors had higher yields compared to the commercial trough planter system irrespective of the crop combinations for the particular prototype. Because the gardening prototypes used a cabinet drawer-system, so the prototypes cannot be placed directly adjacent to each other when deployed, otherwise the drawers cannot be opened for maintenance and other purposes. (In theory, the cabinets can be oriented such that the drawers face inwards to the corridor, but because of fire safety rules, each corridor must allow at least 1.2 m of gap. To allow sufficient gap, the cabinets must be oriented such that the side faces the corridor). In contrast, the trough planters can be placed next to each other. Despite this disadvantage, the vertical corridor gardening prototypes could potentially achieve an average yearly yield of 5.1 ± 1.8 kg m^{-1} (mean ± SD), with Cabinet 5 (Table 2A) having the highest potential yield of 7.7 kg m^{-1}. The average yield of the trough planter system was 0.8 ± 0.2 kg m^{-1} before the consideration of the difference in DLI at the different locations (Table 2B). After considering the differences in the DLI at the different locations, the corridor gardening prototypes still performed better as one unit increase in the DLI would lead to a 0.6 kg m^{-1} increase in the production for the corridor gardening prototypes on average, while for the trough planter system, it would only be 0.1 kg m^{-1}.

Table 2. Results of the growth experiments using the different gardening systems along building corridors and the theoretical yearly yields. A) For the location where the vertical corridor gardening prototypes were placed, the average DLI was 9 mol m^{-2} d^{-1}. The yield for sweet potato vines also included the storage roots harvested at the end of the experiment. B) For the trough planter system, there were eight planters placed at each location with the same vegetable grown in all eight troughs (n = 8). The yield per trough is expressed as mean ± SD. For Chinese mustard, the scientific name is *Brassica juncea*.

A) Vertical corridor gardening prototype	**Cabinet 1**	**Cabinet 2**	**Cabinet 3**	**Cabinet 4**	**Cabinet 5**
Tier 1 (Top)	Choy sum	Water spinach	Chinese spinach	Water spinach	Water spinach
Tier 2	Malabar spinach (red)	Sweet potato vine (purple)	Malabar spinach (green)	Sweet potato vine (green)	French bean
Tier 3	Pumpkin	Cucumber	Bitter gourd	Cucumber	Snow pea sprouts
Tier 4	Winged bean	Long bean	French bean	Winged bean	Oyster mushroom
Tier 5 (Bottom)	Compost	Compost	Compost	Compost	Compost
Growth period (days)	90	90	90	90	55
Total yield (g)	831	537	1314	1079	1002
Prototype yearly theoretical yield (kg)	3.4	2.2	5.3	4.4	6.6
Yearly theoretical yield (kg m^{-1})	3.9	2.5	6.2	5.1	7.7
B) Trough planters	**Location 1**	**Location2**	**Location 3**	**Location 4**	**Location 5**
Geographic coordinates	1.314978N, 103.869995E	1.316898N, 103.875993E	1.352916N, 103.959891E	1.314505N, 103.764751E	1.396613N, 103.746772E
DLI (mol m^{-2} d^{-1})	10	3	11	3	13
Vegetable grown	Water spinach	Pak choy	Chinese mustard	Chinese mustard	Sweet potato vine (green)
Growth period (days)	60	60	60	45	50
Yield per trough (g)	103 ± 26	39 ± 19	110 ± 35	25 ± 8	29 ± 5
Yearly theoretical yield per trough (kg)	0.6	0.2	0.7	0.2	0.2
Yearly theoretical yield (kg m^{-1})	1.3	0.5	1.3	0.4	0.4

The rooftop site for the experiment experienced strong sunlight and the average DLI was 27 mol m^{-2} d^{-1}, which is much higher than the threshold level set under Section 2.4 (16 mol m^{-2} d^{-1}) above which light would no longer be the limiting factor of crop growth. The four species responded differently to the polyculture and monoculture treatments (Fig. 3A). Basil and mustard tended to perform better in a monoculture, with the average fresh weight of individual basil and mustard plant grown in monoculture being more than double of those grown in polyculture ($p < 0.001$ for basil and $p = 0.002$ for mustard). In contrast, okra performed better in a polyculture with an average shoot fresh weight of 67 ± 22 g (mean ± SD) in polyculture treatment compared to 39 ± 13 g in monoculture ($p < 0.001$). Peanut did not show any significant difference between the monoculture or polyculture treatments ($p = 0.321$).

The results of the façade experiment showed that the yield decreased as the growth cycles progressed. Additionally, the interaction between the experimental round and the direction of the façade was significant ($p < 0.001$), which means that the relative yield of the four façades changes with the experimental round. During the first two rounds, lettuce plants grown on the south façade had higher average fresh weights than those on the north façade, but by round 3 the two façades performed similarly, and for rounds 4 and 5, the south façade performed better (Fig. 3B). The east façade consistently produced high yields while west façade produced low yields (Fig. 3B). On average, the fresh weight of individual lettuce plants was 64 ± 23g, with experimental round 1 having the highest fresh weight at 94 ± 41 g and round 5 having the lowest at 30 ± 18 g. The interaction term between experimental round and the presence of balcony was not significant ($p = 0.447$), and the interaction term between the direction of the façade and the presence of the balcony was not significant ($p = 0.331$). The presence of balcony reduced the average fresh weight of lettuce plants from 69.8 ± 1.9 g to 59.3 ± 2.8 g ($p < 0.001$). The average DLI of the experimental period for the façade experiment was 13 mol m^{-2} d^{-1}.

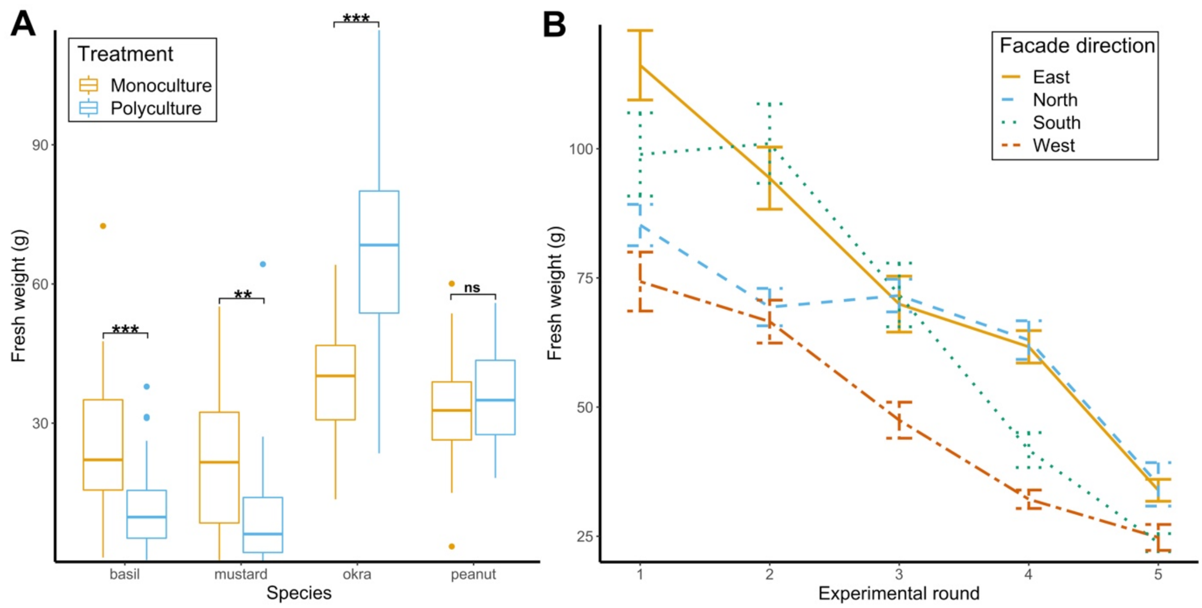

Fig. 3. A) Boxplots to compare the crop growth in the monoculture and polyculture treatments for the rooftop experiment (n = 36). For all four species (i.e., basil, mustard, okra & peanut), the individual shoot fresh weight was used. ** represents p = 0.002, *** represents p < 0.001, ns represent non-significance. B) Change in the average fresh weight of lettuce across the experimental rounds and the different façades (n = 12). The error bar represents standard error.

3.2. Theoretical production from a public housing apartment building

The potential production from corridor gardening, rooftop gardening and façade gardening was calculated based on the assumptions in Section 2.4. Among all the corridors and facades, only the ground storey of corridor A had a simulated DLI marginally below 6 mol m^{-2} d^{-1} at 5.9 ± 0.6 mol m^{-2} d^{-1}, so it was excluded from the calculation. Among the three home gardening methods (corridor, rooftop, and façade), corridor gardening was considered to be the most feasible while façade gardening was the least, based on their accessibility and the current practices in Singapore. Therefore, various scenarios were created to reflect this preference (Table 3). For the corridor farming, both the corridor gardening prototype and the commercial trough planter system were considered. For rooftop gardening, the average fresh weight of a basil plant in the monoculture treatment (24.80 ± 15.30 g) was used for the calculation because of its high yield and that it can be consumed as a vegetable. The yearly unit yield was then estimated to be 3.45 kg m^{-2} based on an estimated growth cycle of 42 days and year-round production. For façade gardening, the average fresh weight of lettuce grown in the first experimental round was used in the calculation.

Table 3. Estimated yearly production level and % self-sufficiency based on the different scenarios.

Vertical corridor gardening prototype	**Scenario 1**	**Scenario 2**	**Scenario 3**
	Corridor gardening	Corridor gardening + rooftop gardening	Corridor gardening + rooftop gardening + façade gardening
Theoretical yearly production (kg)	232	1,584	21,528
% self-sufficiency	0.5	3.4	46.4
Trough planter system	**Scenario 4**	**Scenario 5**	**Scenario 6**
	Corridor gardening	Corridor gardening + rooftop gardening	Corridor gardening + rooftop gardening + façade gardening
Theoretical yearly production (kg)	40	1,392	21,337
% self-sufficiency	0.1	3.0	46.0

After considering the simulated DLI along the corridors and façades, the potential production level for the different scenarios was obtained. The vertical corridor farming prototype (Table 3: Scenario 1) had five times the production of the commercial trough planter system (Table 3: Scenario 4), but the potential contribution of corridor gardening to self-sufficiency level was rather minimal at 0.5% and 0.1%, respectively for the two corridor gardening systems. The potential contribution of rooftop gardening using basil monoculture was higher at 2.9%, but the contribution of façade gardening would be the highest at 43.0% (Fig. 4). The highest level of self-sufficiency achievable using corridor gardening prototype, rooftop gardening, and façade gardening would be 46.4% (Table 3: Scenario 3), meaning the amount produced could potentially be sufficient to meet 46.4% of the total vegetable demand of the estimated 488 residents staying in Block 633 or the amount of vegetables produced could be sufficient to feed 46.4% of the residents, so for each resident, 5.83 m^2 would be needed to fulfil the vegetable requirement of an average resident (building area was estimated to be 1320 m^2).

For Scenario 3, a total of 21,528 kg of vegetables can be theoretically produced yearly, which is equivalent to a yearly unit productivity of 16.31 kg m^{-2}.

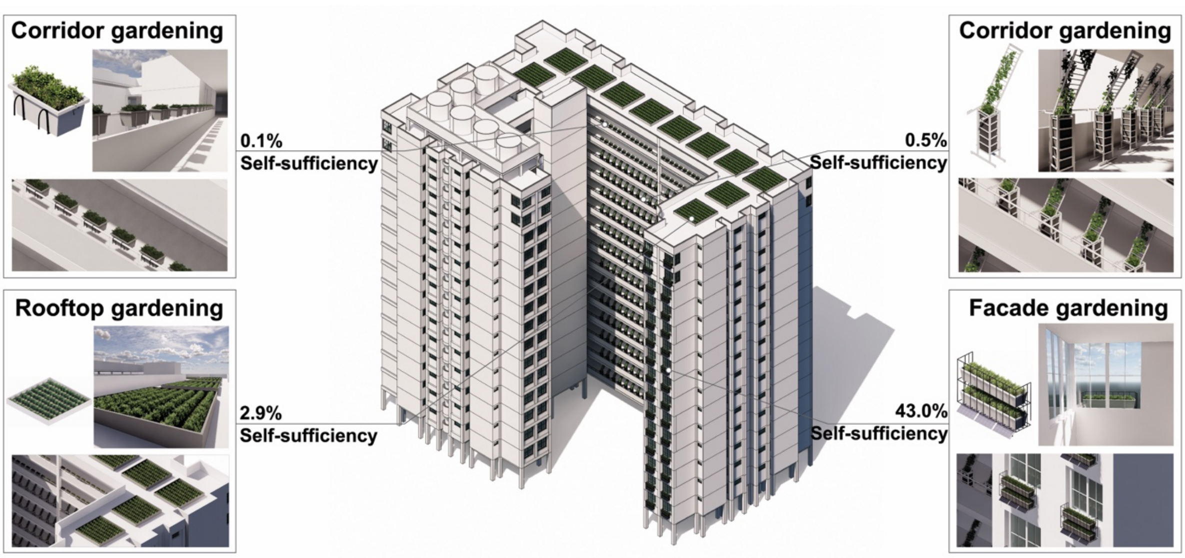

Fig. 4. An illustration showing the level of self-sufficiency achievable by the different gardening methods. The illustration is not drawn to scale. In the calculation, it was assumed the façade gardens would be installed on windowless façades as well and theoretically accessible via external scaffolds without substantial building structural alteration.

4. DISCUSSION

This study investigated the potential vegetable production level in a public housing apartment building using corridor, rooftop, and façade gardening while considering the differences in the light levels received at different floors of the apartment building.

4.1. The different home gardening practices

Between the two corridor gardening systems, the corridor gardening prototype performed better than the trough planter system, most likely because it better utilized the vertical space of the corridors. In particular, the cabinet with snow pea sprouts (Table 2 Cabinet 5) had the highest yield, as sprouts require relatively low levels of light or no light at all and have shorter growth cycles compared to fully grown vegetables (Di Gioia et al., 2017). Nevertheless, given the relatively small area and the low-light levels of corridors, the contribution of corridor farming to the overall production of the building was limited to only 0.5% of the residents' total needs for vegetables.

It was expected that the use of polyculture for the rooftop growth experiment would improve the yield and reduce agricultural inputs (Adamczewska-Sowińska & Sowiński, 2020), and some studies have shown that the productivity may be positively correlated to plant diversity (Haddad et al., 2011; Reiss & Drinkwater, 2018), while others did not find any significant relationship (de Aguiar et al., 2013). In our experiment, the fresh weight of basil and mustard grown in monoculture treatment was significantly higher, while the fresh weight of okra in monoculture treatment was significantly lower (Fig. 3A), which indicates strong interspecific competition. Our results are similar to those of Ropi et al. (2020) in which water spinach preferred monoculture and okra preferred polyculture, so the benefits of polyculture may be species or cultivar specific, depending on if the species selected have complementary traits. In terms of the productivity of the extensive rooftop gardening practice, a growth experiment using an intensive rooftop gardening system (medium depth > 15 cm) in the tropical Yogyakarta, Indonesia, achieved a maximum unit yield of 45 t ha^{-1} or 4.5 kg m^{-2} for Chinese cabbage (Utami & Jayadi, 2011), while in our study using the extensive rooftop gardening practice (medium depth < 15 cm), the highest unit yield was 3.5 kg m^{-2} for basil and for mustard, the estimated unit yield was 3.01 kg m^{-2}. It is expected the intensive gardening system would produce a higher yield because the growth condition is generally more desirable with the additional space for root development and water retention (Schultz et al., 2018). In Barcelona, a polyculture rooftop soilless garden could produce 10.6 kg m^{-2} vegetables a year (Boneta et al., 2019). Nonetheless, an organic intensive rooftop garden, Brooklyn Grange, produces 1.83 – 2.17 kg m^{-2} yearly. Although the yield of rooftop gardens varies because of the gardening practices used, the extensive system used in this study is capable of producing reasonable yield especially given that it has the advantage of light weight compared to relatively heavy hydroponics systems, greenhouses as well as intensive gardening system, which makes it more suitable for more retrofitted building rooftops with limited roof loading capacity.

The reduction of the lettuce fresh weight across the experimental rounds (Fig. 3B) was likely a result of the degradation of the cocopeat-based growing medium as the medium was not changed throughout the experimental period, as well as the presence of pests in the later rounds. To maintain high productivity, it may be necessary to change the growing medium often especially if soilless growing medium is used, which would require more resources and time spent. The wall façades also experienced higher yields compared to the balcony façades, possibly because the wall façades could reflect light which benefitted plant growth. Among the four façades, the west facing façade always had the lowest lettuce plant fresh weight while that facing east tended to have fresh weight on the higher end (Fig. 3B). This is because lettuce generally prefers cool temperature (Fazlil Ilahi et al., 2017) and in Singapore, the morning temperature is lower than the afternoon temperature (Priyadarsini et al., 2008). Given the large surface area of the façades and the promising yield (capable of meeting 43% of vegetable demand of the residents in our study), the gardening and farming potential of building façades should be studied in depth, especially how to improve the accessibility of the vertical space along building façades. A survey among experts in horticulture and building integrated photovoltaic technologies in Singapore has provided a series of recommendations to improve the original design and accessibility of the productive façade prototypes in combination with solar panels, such as using safety grill and façade openings (Tablada et al., 2020).

In addition to the design and the environmental challenges, rooftop and façade gardening may also face competition from solar panels, as the same spaces are often suitable to install solar panels as well. The use of solar panel integrated vertical gardening system may provide a solution to better harness the solar energy received by a high-rise building (Tablada & Zhao, 2016; Tablada et al., 2018).

4.2. Role of the government

With the frequent reports of overseas food scares and the disrupted food supply chains during the COVID-19 pandemic, local produce has been gaining popularity in Singapore (Lim, 2015; Laborde et al., 2020). Given that commercial local produce is generally 15–30% more expensive than imported vegetables and fruits (P. Barber, personal communication, 16 March 2021), fresh produce from home gardens by the residents could potentially be a popular source of food. Given that home gardening may meet 46.4% of the residents' demand for vegetables, the local government can take the opportunity to promote home gardening to improve its food security and food system resilience. Nevertheless, the issues associated with home gardening in apartment buildings need to be addressed before the vertical space can be used safely and efficiently for food production. Vegetables, especially fruit vegetables, grown along the vertical space of an apartment building may become killer litter and endanger the lives of passers-by below if the vegetables grow beyond the external walls of the building and are not secured properly to the growing systems (Jacobs & Cairns, 2011). Corridor gardening may obstruct easy passage during fires if the corridor is narrow and the planter system used is bulky (Ong, 2019). The façade prototype used in this study may be hard to access from inside of a unit, especially for the wall façade (Fig. 1C), and further optimization would be needed to make the design applicable to actual building façades, such as the testbed vertical garden at Tampines Block 146 (Zheng, 2022). The Singapore Food Agency (SFA), the government agency in charge of Singapore's food supply, has been test-bedding the use of a retrofitted residential building façades to grow vegetables with easily accessible planters and translucent shelters (Temasek Foundation, 2021). Although the translucent shelters serve as a protective layer, they also reduce the amount of light received by the plants, and complementary lighting is required. The shelters may also reduce ventilation and increase the microclimate temperature (Sergeeva et al., 2020). Therefore, the design of the gardening systems would play a key role in its safety. It may be necessary for the local government to test the home gardening systems and to develop a protocol for the implementation of the home gardening systems on a large scale. The government can also designate vertical spaces of buildings for home gardening to prevent it from being used for other purposes. It would be a better option to design apartment buildings with home gardening in mind (so called building-integrated agriculture), and by doing so, less effort to retrofit the building for home gardening would be needed in the future. The development and use of analytical models to select for suitable design and technology solutions may also facilitate the process of integrating home gardening into buildings (Ivanova et al., 2020b).

Residents' willingness to participate in home gardening to grow edibles also deserves attention. Home gardening, or gardening in general, has been promoted as a beneficial activity for older adults (Machida, 2019; Maria Aditia & Sholihah, 2019; Kim et al., 2020), and it was observed that gardening may be more popular among older adults than younger adults (MØller, 2005). In Singapore, a door-to-door survey showed that 25% of the respondents were uninterested in home gardening in high-rise apartment buildings, and the younger the respondents, the less willing they were to spend time on gardening, i.e., for adults in the 21–30 age group, they were only willing to spend 1.25 h on gardening a week (Kosorić et al., 2019). Using smart growing systems may help residents to save time

(Halgamuge et al., 2021) and in turn encourage more people to participate in home gardening. Some residents in Singapore also have the stereotypical view that gardening is for older adults (Song et al., 2020). Furthermore, some residents also prefer to grow ornamentals rather than edibles for the aesthetic values of ornamental plants (Oh et al., 2018). To encourage home gardening, the Singapore government has been distributing seeds of vegetables to households (Thiagarajan, 2020). More effort should also be spent encouraging school gardening, especially food gardening in schools for young children, because childhood experiences in gardening may be associated with interests in gardening at the later stage in life (Kingsley et al., 2019).

4.3. Limitations

The theoretical yield obtained in this study was a yearly average for one particular apartment building in Singapore, and depending on the time of the year, the orientation of the façades and the typology of the apartment buildings, the yield per harvest may fluctuate drastically, and the home gardens may not be able to supply vegetables to the residents continuously throughout the year. One resident of Block 633 who stays along Corridor B informed us that Corridor B only receives sunlight for half a year, which means for the other half the year, the amount of vegetables produced would be largely reduced from corridor gardening. The presence of architectural elements, such as windows and overhangs, also affects the amount of light received by the building surfaces. Additionally, the vegetables we used in the calculation are mainly leafy greens, which tend to have higher annual yields compared to fruiting crops. If, in reality, the home gardeners chose to grow other types of vegetables they prefer, the yield may not be as high as what we predicted. We also assumed minimal plant growth when DLI < 6 mol m^{-2} d^{-1}, but sprouts, microgreens, and mushrooms can still grow under low-light condition, and the simulated DLI can be used to select suitable vegetables for the different floors and façades to minimize plant mortality caused by insufficient sunlight and to increase yield.

The results of this study may not be generalizable to temperate cities. Singapore is located near the equator and experiences tropical climate. The annual total rainfall in Singapore is 2165.9 mm, the daily maximum temperature does not usually rise beyond 33 °C and the minimum temperature does not usually fall below 23 °C (Meterological Service Singapore, n.d.). Therefore, Singapore's climate is generally favorable for year-round vegetable production. In contrast, temperate cities experiences winter and the DLI would be much lower compared to summer. The temperature may decrease to a level that may no longer be suitable for vegetable production, but the same experimental approach can still be applied to estimate potential production of a building in the temperate region. Nevertheless, the use of greenhouse may be necessary in temperate cities to ensure year-round production, but the floor loading limit needs to be considered if such greenhouses are to be installed on retrofitted public housing buildings.

Ideally, a cost-benefit analysis should be conducted to understand the economic viability of the different types of home gardens in public housing buildings taking into consideration the gardening material cost, the cost to retrofit the building as well as the manpower cost. However, this study is a proof of concept to show the feasibility of the different types of home gardens in high-rise residential buildings, making use of the corridors, roofs and façades. The corridor and rooftop prototypes used in this study were not available in the market and the additional building structural support required for accessibility and safety (such as the scaffold required to access the façade gardens along windowless walls) was also excluded in the study, making a reasonable estimation of the cost difficult. A recent study by

Tablada and Kosorić (2022) suggested that home façade gardens can be accessed via platform overhang or scaffold and in addition to conventional planting beds, horizontal hydroponics channels, hydrophilic planting beds and vertical planting beds can be tested on façades. Additionally, the environmental sustainability aspect of high-rise home gardening was excluded from this study. If more residents adopt the high-rise home gardening practices, the amount of resources required in terms of water, electricity (in the form of supplementary lighting or automation), and fertilizer would increase. A circular economy approach to convert urban waste into useful agricultural materials can potentially improve the environmental sustainability of high-rise home gardening, such as converting household food waste into fertilizers using black soldier fly larvae (Song, Ee, et al., 2021) or anaerobic digestion (Song, Lim, et al., 2021). Future studies can implement the different designs and compare their productivities, accessibility, environmental sustainability as well as the cost of the whole system.

Although this study demonstrates that home gardens in public housing blocks can provide fresh produce despite the small area, it is also important to consider the food safety and nutritional requirement of the populations and not to focused only on the quantity of vegetables produced alone, especially given the relatively high air pollution levels in cities which may result in pollutant accumulation in crops (Amato-Lourenco et al., 2017) and negative public health consequences (Rai et al., 2019). Because most of the public houses are located near roads, the accumulation of pollutants on crops may be a concern. Lettuce and basil have been shown to accumulate heavy metals if the soil is contaminated (Antisari et al., 2015). Different vegetables also accumulate heavy metals at different rates (Troch, 2016). Therefore, it is important to ensure the growing medium used by home gardens is low in heavy metals to minimize the heavy metal content in vegetables (Arrobas et al., 2017).

Important dietary components, such as chicken and fish, were excluded from the analysis of this study as well, because fish and poultry farming is currently prohibited in public housing estates owing to animal welfare concerns as well as the inconvenience it can cause to the neighbors (Wong, 2019). Because home gardens in public housing blocks often face light and space constraints, only certain vegetables may be suitable, such as leafy greens, so the diversity of the vegetables produced may be limited. The amount of food produced in home gardens can be greatly reduced if there is vandalism or theft, especially if the home gardens are also accessible to other residents. One way to reduce the occurrence of vandalism or theft is to encourage residents to participate in home gardening and to exchange their fresh produce with each other.

5. CONCLUSIONS

In addition to its environmental benefits, vertical greenery along high-rise apartment buildings may help to improve urban food security as well. This study is the first study to systematically estimate the food production potential of a high-rise public housing apartment building using an experimental approach. We assessed three home gardening methods, namely corridor, rooftop and façade gardening by considering light availability. Our results showed that home gardening can potentially meet 46.4% of the residents' need for vegetables. Although corridor gardening is often practiced in Singapore, it has the least contribution to the self-sufficiency level achievable at only 0.5%, as the corridor space and the sunlight received along corridors are often limited. Rooftop gardening and façade gardening has a higher potential to achieve 3 and 43% of the self-sufficiency level. This study showed that building façade has great potential as home gardens but faces the accessibility issue among other problems. The challenges faced by Singapore in terms of the design of the vertical gardening spaces and the relatively poor participation rate of the residents in home gardening may also be experienced by other cities. Future work should focus on improving the design of vertical space gardening systems for high-rise buildings and encouraging residents to participate in home gardening. Improving environmental sustainability and ensuring food safety in terms of crop pollutant accumulation in home gardens are other aspects of interest. Models can also be developed to select suitable home gardening designs and crops based on the environmental conditions experienced by a building.

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