JOURNAL

OF LIVING ARCHITECTURE

A GREEN ROOFS FOR HEALTHY CITIES PUBLICATION

Volume 6 Number 2 Pages 1-16

2019

Rooftop urban agriculture for the small stakeholder

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ABSTRACT

Urban agriculture (UA) has the potential to benefit inner-city communities, by reducing food transport distance, increasing awareness of how food is produced, and by improving the nutrition, health, and economic status of the same communities. In this study, green beans, cantaloupe, eggplant, squash and tomatoes were grown in a rooftop garden. Results indicate that water source quality and rooftop climatic conditions (solar induced temperature rise) can present limitations to the success of untrained rooftop gardeners. Some outreach and educational materials on how to overcome obstacles will be necessary to help untrained UA farmers establish productive gardens on the rooftop environment.

Key words: urban agriculture, rooftop garden, nutrition, community

INTRODUCTION

There have been an increase in the calls for the inclusion and integration of rooftop agriculture into the future of urban agriculture (UA) planning and research in recent years (Whittinghill and Rowe, 2012; Buehler and Junge, 2016; Boehm, 2017). This subset of UA has been characterized as urban rooftop farming, zero-acreage farming (Zfarming), or as agriculture in and on buildings (AOIB). Historically, soil-based UA has been the most visible and commonly practiced form of agriculture in the urban environment. The use of surface-level space and soil has also been the focus of a great deal of research, while the potential use of rooftops to produce fresh vegetables, poultry, and eggs has been largely overlooked until very recently (Cohen et al., 2012; McClinton et al., 2013; Mok et al., 2014). There are major climatic and biome/micro-biome differences between rooftop and surface environments. However, there are both advantages and limitations for rooftop UA when compared with conventional surface soil based UA that suggest both forms will be important tools in the UA toolbox moving forward.

The movement to devote more resources to UA is borne out of the need to reduce the great distances over which food supply chains are distributed, and to address the need to provide food security in the urban environment as more of the global population becomes concentrated in cities (Grewal & Grewal, 2011; Meenar and Hoover, 2012; Goldstein et al., 2016). The general benefits of UA to urban populations have been reported to include increased access to and consumption of fresh produce in low income neighborhoods, educational opportunities, community wellness, ecosystem services, and employment (Meier et al., 2013; Vitiello and Wolf-Powers, 2014; Eigenbrod and Gruda, 2015; Orsini et al., 2014; Boehm, 2017). While these benefits are well documented, access to open soil in cities can be constrained by physical availability, legal availability, transition through development, and high frequency of unsafe levels of contamination (e.g. brownfields) (Hui, 2011; Whittinghill and Rowe, 2012; Specht et al., 2014). On the other hand, flat roofs can make up 30-85% of the roof space in cities, providing potential and attractive alternative space for the production of food (Specht & Sanye-Mengual, 2015; Boehm, 2017).

It has been argued that the benefits of UA have not been accessed by under-served low-income populations in cities, but have been more often reaped by more well-to-do populations with the income to afford the extra cost and/or investment in the infrastructure required. The Gary Comer Youth Center in Chicago is a notable exception (Proksch, 2011). Recent reviews cover few examples of rooftop UA focused on low-income people (Guthman, 2008; Thomaier et al., 2014). Most projects reviewed have been located in areas of well-educated middle-income, or higher-income, populations. Bohm (2017) confirmed that AIOB projects producing food in North America do not serve areas of extreme poverty; however, there are a few practices in Germany, where unemployed adults can receive UA training and marketable skills (Kosack, 2012; Eigenbrod and Gruda, 2015).

Engagement in rooftop UA by low-income populations will probably first be realized by individuals and small groups of tenants living under the roof to be used for food production.

These represent small stakeholders in UA, putting in their own time and resources to grow better food. However, a certain level of horticultural expertise is required to manage and maintain a soilless media, open-air production system. Some training will be required to facilitate early success. Many small stakeholders, therefore, will benefit from outside assistance in either funding, education, or both. Research providing technical details of the pathways to success and obstacles to avoid is unfortunately not well developed.

An important discussion in the available research concerns the trade-offs between plant growth media designed for extensive green roof (< 15 cm in depth) runoff control and media designed for edible vegetable production (Walters and Midden, 2018). Traditional green roof media performs poorly for vegetable production, yet potting soils that grow vegetables well are not efficient at controlling leachable nutrients (Elstein et al., 2006; Grard et al., 2015; Aloiso et al., 2016). Eksi et al. (2015) showed that additions of compost to extensive green roof media up to 60-80% of the substrate mass improved yields of cucumbers and peppers, but may exceed recommendations for standard green roofs designed for storm water control. The shallow depth of substrate used in conventional extensive green roofs is constrained by physical structural capacities and will limit vegetable production to those species that can adapt to and/or tolerate shallow root depths (Elstein et al., 2006). Ouellette et al. (2013) cited shallow depths (7.5 to 10 cm) as a primary factor reducing tomato yield and quality, with total harvested edible biomass of 1 to 7 kg per plant by treatment. These authors also stressed the importance of beneficial micro-organisms to increase root growth. McGuire et al. (2013) reported that fungal communities in green roof systems were functionally different than those found in ground level park soils. Molineux et al., (2014) reported that inoculation with mycorrhizal fungi and compost teas containing live organisms enhanced plant performance. However, there was an antagonistic effect when both were added to the same substrate.

Many production rooftop farms and research into the subject have been located in the cooler regions of the U.S. and Europe. The effect of high heat loads on roofs in warmer climates without cold winters is not well represented in this research. However, Jim (2014) found that green roofs in warmer climates experience far greater net heat loads in summer and winter than those reported by others in cooler regions, such as Michigan (Whittinghill et al., 2013; Eksi et al., 2017). What affects a warmer climate has on rooftop vegetable production has not been specifically covered well to date. Finally, the effect of irrigation water quality has not been reported on in the literature supporting roof top agriculture, although general horticulture research has many examples of recommendations for pH, total dissolved solids (TDS), and/or specific nutrient or toxicity limits (Niu and Cabrera, 2010).

In this study, a facsimile of a low-input small stakeholder system using publicly available and inexpensive resources was recreated to investigate the potential for success. In order to simulate the low-input small stakeholder system, inexpensive and commercially available equipment and materials were used in our study. Every effort was made to utilize publicly available information to provide guidance on plant production practices for the home gardener (e.g. cooperative extension publications). The results of physical, biological, and chemical measurements taken during a growing season in southern central Texas for a

rooftop vegetable garden are presented, along with a summary of observations related to some likely obstacles facing the do-it-yourselfer intent on breaking the low-income barriers to rooftop UA.

METHODS

A rooftop fruit and vegetable garden was installed on the roof of the four-story Langford Building on the campus of Texas A&M University (3137 TAMU, College Station TX; 30.678791, -96.337690) in March of 2017. The garden utilized twenty-seven modular plastic green roof trays (TectaAmerica Corp, Rosemont, IL) that were installed on the roof in three square arrays of 9 modules each (Fig 1) in November, 2012. Each individual module was 61 cm x 61 cm, and was filled with FLL-compliant growth media (Rooflite®, Skyland USA LLC; Landenberg, PA) to a depth of approximately 9 cm. For the current study, the media was 5 years old and had been used to grow a variety of plant species to be evaluated for suitability for use on green roofs. More details on the history of the modules and plants can be found in Dvorak et al. (2013).

In March of 2017, winter weeds and any remaining plants from previous studies were hand-removed from 25 of the 27 modules. Two modules containing garlic chives were left in the third array as the root systems were too extensive to separate from the media. Fruits and vegetables were planted in the 25 remaining cleared modules. These 25 modules were arranged as a randomized complete block study as follows: the first species (treatment) was planted in the lower left plot (Figure 1) followed by species 2 and 3 to the right. Species 4 and 5 were planted in the next two modules above this in the left hand and center plots respectively on the second row. Species 5 was planted in the next available row above and so-on, so that the pattern for filling 5 species blocks was first left to right and then below to above until all available modules were filled with 5 replicates of 5 species of vegetables. The five species selected for their rapid maturity and shallow rooting depth traits were tomato, green beans, cantaloupe, mustard kale, and spinach. Seeds were started in 15 cm Ray Leach Cone-tainers (SC10r; Steuwe and Sons, Inc; Tangent, OR) in starter media and transplanted after 3 weeks. Tomatoes and beans were supported using 60 cm bamboo poles. Kale, spinach and tomatoes were replaced by eggplant, squash, and a new set of tomato plants following an extreme wind event that severely damaged the three crops within two weeks of planting. The replacement plants were purchased from a local garden center and wire cages were placed on and anchored to the individual modules containing beans, tomatoes, and squash to minimize future damage.

At the initial planting, commercially available granular multi-nutrient fertilizer (*ultraGreen* All-Purpose Plant Food, Pennington Seed, Inc., GA) containing 10% nitrogen (N), 10% phosphorus (as P₂O₅), 10% potassium (as K₂O), 3% calcium (Ca), 0.02% boron (B), 0.10% iron (Fe), 0.05% manganese (Mn), 0.0005% molybdenum (Mo), and 0.05% zinc (Zn), was applied at a rate of 12.2 g m⁻³ (2.5 lbs 1000 ft⁻²) as per Masabni (2014). Two additional applications of urea fertilizer (46% N only) were applied at a rate of 3 g m⁻³ in mid-April and mid-May 2018.

Figure 1 (Center) Layout of roof modules (TectaAmerica Corp, Skokie IL) and location of each of the final species. Bn = Green Bean. Cn = Cantaloupe. Eg = Eggplant. Sq = Squash. Grey squares indicate location of garlic chives remaining from previous plantings. (Top left) Wide view of roof vegetable garden in near frame with succulent garden to right of frame and living wall in background. (Bottom left) Tomatoes on scale with bird damage evident. (Top right) Cantaloupe. (Bottom right) Eggplant and tomato harvest.

Three Decagon Devices GS3 Greenhouse sensors (Meter Group; Pullman, WA) with 5.5 cm probes were inserted into the rooftop growth media of the center module of each of the three module arrays to record growth media temperature, water content, and electrical conductivity. Local weather data (temperature and precipitation) was collected from Easterwood Airport (College Station, TX) weather monitoring station located 6.7 km west of the roof site. Growth media temperature was collected as mean, high, and low temperatures every 24 hour period. Precipitation was collected as daily total (mm). Data from the GS3 sensors was collected at a rate of 96 points per 24 hour period (12:00 am to 11:59 pm). The mean of the three modules' media temperatures was calculated for each 24-hour period, as were the high and low temperatures.

Prior to planting and following the final harvest of vegetables and fruits for this study, the growth media was sampled for plant available nutrient status. Media was sampled pre-season by compositing 3 cores from each module into a single sample representing each of the three nine-module arrays. Post-season media was composited from each module into 25 samples representing. Saturated media extracts (SME) were prepared by adding de-ionized water to 200 g of dry media to the point where a sheen was just visible at the surface (Sims and Wolfe, 1995). The media was stirred, allowed to settle, and water replaced as needed to observe the sheen again. The saturated media was allowed to equilibrate for 30 minutes before filtering through 120 mm Whatman no 1 rounds (GE Healthcare, Chicago IL). Filtered leachate was collected and analyzed by ICP-AES for extractable mineral nutrients.

Irrigation water was sourced from the public water system of College Station, TX. Irrigation water was supplied by flexible pvc pipe available at the local garden center and delivered via four directional nozzles at the corners of each module array, as well as one omni-directional nozzle in the center module of each array. All nozzles were placed approximately 35 cm above the module surfaces, and irrigation was applied daily for about 10-15 minutes. Irrigation water quality was measured using a hand-held total dissolved solids (TDS) meter (TDS Testr 11; Oakton Instruments, IL), an Orion benchtop pH meter, and ICP-AES for total mineral nutrients.

A plant health rating system was used to semi-quantify the relative performance of the vegetable and fruit plants grown on the roof. The rating system was composed of 5 levels of observation: 1) dead, 2) near death, 3) alive but not especially healthy, 4) healthy, and 5) fruiting and or flowering. At each date of collection (April 21st, April 28th, May 12th, May 18th, June 5th, June 30th, July 10th, and July 14th), ratings were applied to all four plants in each individual module. Means for all plants in the study are presented. The mass of eggplant, tomato, and cantaloupe were measured by harvesting fresh produce from plants and weighing on an analytic balance within 10 minutes on June 30th, July 10th, and July 14th, 2018.

Biomass for the eggplant above-ground matter was collected by pulling entire plants from the rooftop growing media and cutting the root matter from the top matter at the point where the

plant top emerged from the rooftop media surface. Plant tops were dried in a laboratory oven at 60°C for 48 hours or until constant dry weight was achieved.

Eggplant roots were examined for the presence of arbuscular mycorrhizal fungi (AMF) association after washing carefully in reverse osmosis (RO) water to remove all granular media material. Preparation for AMF examination included boiling 0.5 cm sections of roots (10 from each plant) in 10% KOH (10:90 KOH:Distilled water) for 13 minutes, cooling to room temperature and staining in a solution of weak acetic acid (5% concentration) and black ink (5%) (Pelikan black; Herlitz PBS AG Company; Germany). Clean roots were heated to 95°C for 3 minutes in 5:95 ink:acetic acid, rinsed with RO water with a few drops of acetic acid for 20 minutes, and allowed to cool for observation under 10x magnification. An Amscope microscope (model 1570022; Amscope company; Irvine, CA) was used in conjunction with an Amscope digital camera (8 Megapixels). Images were recorded using the Amscope software installed on a Toshiba Portege Laptop and assessed for the level of AMF infection in roots.

AMF infection was evaluated as a percentage of roots infected and relative maturity of the association between AMF and eggplant roots (Korhonen, Kytöviita, and Siikamäki 2004).

Equation 1 was used to semi-quantify observational data.

$$\% \text{ root infection} = \frac{\text{Sum of Ratings}}{\text{Maximum Possible Sum of Ratings}} \times 100\%$$

The AMF percentage observed under microscope was scored on a scale of 0-5 with some modification from the method described by Suharno et al. (2016) to place more emphasis on the maturity of plant host/AMF interaction, rather than the density of mycelial/hyphal structures alone. Score 0 indicates no hyphae, score 1 = trace to 20% mycelium/hyphae, score 2 indicates 20-60% mycelium/hyphae, score 3 indicates a greater than 60% mycelium and trace amount of (<10%) vesicles and arbuscules, score 4 denotes up to 40% vesicles and/or arbuscules and mycelium, and score 5 was applied if greater than 40% arbuscules and/or vesicles and mycelium. In this scoring system, percentage refers to the area of the root segment showing evidence of fungal structures.

Statistical analysis for pH was performed as paired t-test for initial and final measurements using PROC TTEST in SAS software (SAS; Cary, NC). Paired t-test was not applied to sodium content at initial and final samplings due to only one data point collected as a composite at the initial sampling. Individual values for daily low, mean, and high temperatures between the weather station and the in media roof sensors were compared using PROC TTEST. Plant performance ratings were compared through multivariate analysis using PROC GLM in SAS with the model time of sampling + species + time of sampling x species = mean rating. Differences are only reported in the results if significant at $\alpha = 0.05$.

RESULTS

Plant Performance and Yield

Shortly after installing the first crops on the roof, a high intensity wind event caused irreparable damage to three of the species: tomatoes, kale, and spinach. These were replaced by a new batch of tomatoes, squash, and eggplant respectively. The starter plants germinated in the greenhouse were too fragile at the stem, and the bamboo pole supports were blown away in the wind. Sturdier-stemmed replacements of wire frame square cages tied down for support were more successful in resisting the force of subsequent wind events. Additional N was added 3 weeks afterward when lower leaves of most plants showed early signs of chlorosis (yellowing). This addition of fertilizer N was repeated again 4 weeks later for the same reason. High rainfall during this period (Figure 2) is suspected of leaching N through, and out of the, modules.

Average plant performance ratings increased from April 21 until May 18, 2018, when a gradual decline was observed (Figure 2). Eggplant, and squash plants were consistently the healthiest during this period. Eggplant ratings were 3.4, 3.7, 4.1 and 4.3 for the dates April 21, April 28, May 12, and May 18, 2018 respectively. Squash plant health ratings were 4.0, 4.0, 4.2, and 4.0 for the same dates. As the study period progressed, tomato ratings increased while squash ratings decreased. Eggplant and tomato ratings continued to be the highest through the end of the study, but with steady declines between June 30 and July 14. For the observations made on June 5, June, 30, July 10, and July 14, tomato plant health ratings were 4.5, 4.3, 3.4, and 3.2. Eggplant ratings were 4.6, 3.6, 3.2, and 3.3. Beans and cantaloupe were the poorest performers, with beans completely dying off by June 30.

The overall yield of the produce was low and would not have been equivalent to the time and other resources put into the cultivation and maintenance of the roof top garden. The best performance period was that approaching the end of June, 2018 (Table 1). The total harvest weight of eggplant and tomatoes combined was nearly 2 kg. Eggplant and tomato fruits were both small in size. These fruits were also harvestable on July 10th, though plants appeared stressed and total weights were substantially lower. As the season continued, cantaloupe fruit matured and were harvested on July 10th and July 14th. The cantaloupe harvested were also smaller than expected, as compared to those commercially available.

Table 1 Harvest weights and dates for produce collected during study. Total weight of each species fruit or vegetable at 3 harvest dates. g = grams

Harvest Date	Plant	Total Fruit	Total Mass (g)
June 30, 2018	Eggplant	21	1515
	Tomato	7	209
July 10, 2018	Cantaloupe	1	200
	Eggplant	3	119
	Tomato	6	389
July 14, 2018	Cantaloupe	1	99
	Eggplant	1	23

Evidence of Root-Mycorrhizal Association

Eggplant roots examined for the presence of AMF association revealed a relatively robust level of interaction between root and fungi for a constructed growth media in an environment so far removed from surface soil. Following assessment for % root infection, the observed values ranged from 24% to 52% infection. These values are on par with observations in field grown no-till corn (Thapa et al., 2017) and greenhouse-grown cotton (Mowrer, unpublished results) which ranged from 40%-58% and 11%-66% respectively. This method of observation (Figure 3) allows for a ranking based on the maturity of development of the colonization (Thapa et al., 2017). Although AMF are found in most biomes on the planet (Dodd, 2000), lack of association between roots and AMF on rooftops may portend a poor outcome for vegetable production without deliberate inoculation. This result indicates that, for whatever reason, AMF will likely be able to proliferate naturally on rooftop farms and produce viable associations with the vegetables grown there.

Environmental Conditions

The source water used to irrigate the plants municipally supplied water from the College Station, TX Water Services Department. Municipal water quality reports made publicly available were used for the following data on dissolved nutrients and salts (City of College Station Water Services Department, 2018). No additional water treatment or conditioning system was used in between. Reports from the department indicate pH levels of 8.3-8.5 and total dissolved solids (TDS) concentrations of 500-550 mg L⁻¹ for the previous 4 years (City of College Station Water Services Department, 2018). Historic pH reports were consistent with spot measurements on the roof. However, TDS measurements often exceeded 700 mg L⁻¹ (data not presented). The higher observed concentrations for TDS on the roof may have been the result of changes resulting from the distribution distances within the greater municipal system.

Figure 2 Plant performance ratings from April 21 to July 14 (study termination), 2018. Beans, Cantaloupe, Eggplant, Squash, and Tomato means of ratings from 1-5 shown by vertical bars. Error bars = 1 standard deviation. Grand mean line illustrates the average of all species' performance.

Figure 3 Blue-stained structures found within fine roots of eggplants indicate colonization by vesicular arbuscular mycorrhizal fungi (40x microscope images). Long thread-like structures are intracellular hyphae. Round structures are vesicles, which store nutrients brought to the root from extracellular hyphae in the growing medium. Arbuscules have a branch-like structure and are the main site for exchange of nutrients between the host plant and the fungal organism.

The most recent measurements for Ca and Na in the 2016 report were 3.26 and 222 mg L⁻¹ respectively. The most recent available reports (2014) for bicarbonates and chloride in the municipal water were 442 and 57 mg L⁻¹ respectively (City of College Station Water Services Department, 2018). Sodium and chloride are ions of particular concern for plant injury or growth constriction (Grattan et al., 2003).

From the beginning of the study to the end, pH values in the roof media rose substantially from near neutral values to greater than pH 8 (Figure 4). This change in chemical condition of the media is almost certainly a result of the irrigation water inputs. TDS values, however, were not affected by the irrigation water quality. It is interesting to note however, that there was a marked rise in Na concentrations in the roof media throughout the study (Figure 5.) Many plants can tolerate alkaline pH and elevated TDS irrigation water when sufficient rainfall is supplied to leach salts and neutralize alkaline buildup. However, continued application of moderately high TDS water will cause an accumulation of salts that can damage plants and constrain productivity. Beans, eggplant, squash and tomato are all sensitive or moderately sensitive to salt accumulation (Grattan et al., 2003). While tomatoes may tolerate pH values as high as 7.5, the fruits and vegetables grown in this study perform best between pH values of 5.5 and 6.5, well below the final values measured (Burrows and Graper, 2008). Buildup of bicarbonate ions in the media from the irrigation water is the most likely mechanism responsible for the rise in pH over the study (Bajwa et al., 1983; Park et al., 2016). This condition leads to complexations between bicarbonate and calcium in the media solution, decreasing calcium availability and increasing exchangeable plant available sodium.

Figure 4 Initial and final roof media pH and Total Dissolved Solids (TDS). Subscripts: i = initial, f = final. p = probability of significant difference between initial and final mean values as determined using fisher's protected lsd. Absence of p value indicates no significance. Error bars = 1 standard deviation (σ).

Figure 5 Sodium concentration in saturated media extracts from initial (Na_i) and final (Na_f) roof media sampling events. Error bars for final sampling event = 1 standard deviation (σ). No error measurement available for initial sampling event as only composite samples taken for each vegetable.

Aside from the challenges observed with the chemistry of the plant-growth media environment, climatic conditions on the roof also caused constraints to the health and productivity. Wind events can be more turbulent and destructive with the elevation and lack of protection by trees, buildings and other windbreaks normally found at surface level in the urban environment. However, solar radiation loading on the roof was of the most concern in this study. The black green roof trays, darkly colored media, and surrounding roof environment absorbed more solar radiation than surface soils at the nearby weather station (Figure 6). The average daily temperatures measured on the roof tracked well with the daily averages observed at the nearby weather station. The daily low temperatures at both locations were in even better agreement. However, the high daily temperatures show major differences in early- to mid-May, and again for a nearly continuous period lasting from late May to late June 2017. The daily highs on the roof often persisted for periods of 3-5 hours. The magnitude of difference on many days was between five and ten degrees Celsius. Most severe were the differences in late May and early June of as much as twenty degrees Celsius. During these events, the temperature of the growth media exceeded 40°C, and approached 50°C on two occasions.

Figure 6 Average, low, and high daily temperatures recorded by roof media sensors and at the nearby weather station (WS) for 105 days beginning on April 1, 2017.

Heat stress causes many physiological responses in plants, including reduced photosynthesis and inhibition of fruit production (Rivero et al., 2002; Camejo et al., 2005; Bitá and Gerats, 2013). During this period of extremely high temperatures, plant health ratings decreased in all five species. The problem of high solar absorption and heat stress in plants grown on roofs is one that will need to be addressed in the southern U.S., though perhaps will not be of concern in the northern states.

CONCLUSION

Based on this study, there appear to be potential obstacles to success for the untrained small-scale rooftop gardener. The two most important problems observed in this study were irrigation water quality and solar radiation absorption. There will always be structural limitations to the weight of materials that can be placed on roofs. This will constrain selection of species to those tolerant of shallow growing media volumes. Shallow conditions will lead to rapid loss of water from the media and necessitate frequent irrigation during periods of low precipitation. Therefore, irrigation water quality will need to be tested prior to investment in equipment and materials. There will be scenarios wherein the water source used is of a high quality, and others where a pre-treatment system will be necessary ensure desirable yields of produce.

The problem of heat stress caused by absorption of solar radiation on rooftops suggests adjustments to managing roof top gardens in the southern U.S. will be required. Some protections from high solar radiation inputs are expected to improve outcomes, such as shade cloth above the plant canopy, or reflective cover below the canopy to reduce the effect. Addition of mulches, which can protect from high heat and conserve water in typical surface gardens, may add excessive weight to the rooftop garden. It is suggested that further research be performed to target inexpensive solutions to these problems. Placing the power to produce vegetables on the roof surfaces of urban environments directly into the hands of underserved communities can still lead to reductions in food deserts, increasing both access to higher nutrition density foods and food dignity. However, more focused solutions, outreach, education, and training on rooftop gardening will be necessary to empower communities to use effective, stable, and low cost production systems to bring higher nutrition to the underserved urban table.

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