Plastic Rooftop Rainwater Harvesting Technology in Arid Greenhouse Vegetable Cropping System in Anding, Gansu, China

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Abstract: Several greenhouse vegetable cropping models have been established to deal with the natural, arid, water deficit weather condition in Anding District. Irrigation requirement is computed based on various irrigation schemes. Rainwater harvesting technology is utilized to estimate the water collection amount with the greenhouse plastic rooftop using the water-balance rationale. Different water demand and runoff collection surface needs are determined based on the supplemental irrigation requirements of the various vegetable cropping models using regulatory benefit principle. The required capacity of rainwater storage is then evaluated for each cropping model. These results provide valuable references for rainwater harvesting technology using greenhouse plastic rooftop for agricultural production.

1. Introduction

Along with the rapid development of moderately high standard of living society, modern agriculture in China has to keep pace with and to satisfy the ever increasing “food-basket” demand of the general public. In arid water shortage areas, rainwater harvesting has become more popular, essential and important. In particular, greenhouse plastic rooftop rainwater harvesting technology has developed into an unique feature for agricultural crop production model in water deficit areas. This technology has promoted modern, industrialized, intensified agriculture development in dry areas. It is considered as one of the most innovative, self-sustaining water resource utilization methods. This technology also provides the needed impetus to achieve poverty alleviation, and to reach the ultimate goal of establishing moderately high standard of living society in China.

The main objective of this study is to demonstrate the capability of utilizing this technology on several greenhouse vegetable cropping models. These results should provide valuable references for rainwater harvesting technology using greenhouse plastic rooftop for agricultural production.

2. Study Area

This study is conducted in the Anding District, Dingxi County, in the central part of Gansu Province, China. This district is also located in the middle section of the Loess Plateau, between 35°17′54″ – 36°02′40″ N latitude and 104°12′48″ – 105°01′06″ E longitude (Figure 1). The soil surface is brittle, undulating, with abundant gully formation. The relief is southwest to northeast sloping, between 1,700 -2,300 m above mean sea level. The climate belongs to mid-subtropical arid and semi-arid type. Annual mean precipitation is about 398.5 mm and concentrated in summer and fall months. The highest rainfall falls between June to September and comprises about 67.2% of the total annual rainfall. Evapotranspiration reaches as high as 1,500 mm per year [1]. Water supply is extremely limited due to...
scanty rainfall amount. Agricultural production, relies solely on natural rainfall, a typically rainfed agricultural district and extremely high demand for water resource development. Rainwater harvesting technology becomes the basic supplemental irrigation water supply for agriculture. This technology also provides strong support for agricultural development in greenhouse facilities.

3. Main Cropping Models and Irrigation Schemes in Greenhouse

3.1. Main Crops
Currently, the main crops grown in greenhouses are high altitude, summer vegetable crops that include: eggplant, pepper, tomato, cucumber, and pumpkin. Post-harvest fallow, short vegetable crops consist of: rape, cabbage, and spinach are usually grown in fall-winter seasons. Some large scale farms grow ornamental plants for recreational purposes. There are a few new variety strawberry and peach farms. However, they are of small scale and cannot be regarded as part of the main crops in this area.

3.2. Cropping Models
Planting date for the main transplant crops including: eggplant, pepper, tomato, cucumber, and pumpkin is in the mid-April month in the greenhouses in Anding District. Harvesting usually ends in the middle of September. To enhance higher land use efficiency, after post-harvest of the main crops, short transitional vegetative crops such as rape, cabbage and spinach are planted in the middle of November and harvested in early January during the fallow period. Seed-bed preparation along with fertilizers and insecticides application are performed after the second harvest, readying for the second vegetation cropping cycle. Vegetable cropping models in Anding District are shown in Table 1.

| No. | Cropping model       | Main vegetable crop Start | Main vegetable crop End | Green leaf vegetable crop Start | Green leaf vegetable crop End |
|-----|----------------------|---------------------------|-------------------------|--------------------------------|-----------------------------|
| 1   | Eggplant plus FWGLV* | Mid-April                 | Early-mid September     | Mid-November                   | Early January               |
| 2   | Pepper plus FWGLV    | Mid-April                 | Mid-late September      | Mid-November                   | Early January               |
| 3   | Tomato plus FWGLV    | Mid-April                 | Mid-late September      | Mid-November                   | Early January               |
| 4   | Cucumber plus FWGLV  | Mid-April                 | Early-mid September     | Mid-November                   | Early January               |
| 5   | Pumpkin plus FWGLV   | Mid-April                 | Mid-late September      | Mid-November                   | Early January               |

*FWGLV = Fall-winter green-leaf vegetable
3.3. Irrigation Schemes
High efficient drip irrigation system is used for the main vegetable crop production, whereas furrow irrigation system is used for the fall-winter green leaf vegetable crops (FWGLV). Previous study results indicate that water use intensity by eggplant and pumpkin crops is much less. Water requirement is about 2.0 – 2.5 mm/d. Requirement for pepper, tomato and cucumber is about 2.5 – 3.0 mm/d [2]. In Anding District, total irrigation amount for the main vegetable crops is usually set at 135 mm/interval. Irrigation frequency and amount depends on the season as well as different growth stages. The normal irrigation frequency is about 5 -10 days. However, during early growing stages, irrigation is less frequent at 12 -13 days’ intervals. FWGLV’s irrigation amount and irrigation interval is set at 180 mm/interval and 15 days, respectively.

In accordance to the above previous study results, cropping scheduling, the current climatic conditions and vegetable irrigation practices in Anding, the simulated irrigation schemes for various vegetable cropping models are shown in Table 2.

Table 2. Irrigation schemes for various vegetable cropping models in Anding District.

| Cropping model | Planting period (Month/day) | Irrigation intervals | Irrigation amount/Interval (mm) | Total irrigation amount (mm) | Water use intensity (mm/d) Minimum | Maximum | Average |
|----------------|----------------------------|----------------------|-------------------------------|-----------------------------|----------------------------------|---------|---------|
| Main vegetable crop | Eggplant | 4/10 – 9/10 | 18 | 135 | 2430 | 1.0 | 2.5 | 1.58 |
| Pepper | 4/10 – 9/20 | 22 | 135 | 2970 | 1.5 | 3.0 | 1.81 |
| Tomato | 4/10 – 9/20 | 24 | 135 | 3240 | 1.5 | 3.0 | 1.98 |
| Cucumber | 4/10 – 9/20 | 24 | 135 | 3240 | 1.5 | 3.0 | 1.98 |
| Pumpkin | 4/10 – 9/10 | 19 | 135 | 2565 | 1.0 | 2.5 | 1.67 |
| FWGLV | 11/10 – 1/10 | 4 | 180 | 720 | 1.0 | 2.0 | 1.16 |

4. Greenhouse Area and Irrigation Requirement
4.1. Greenhouse Structure and Area
Greenhouse facilities become popular for modern and efficient agricultural production development. Vegetable grown in greenhouses has provided “food basket” security for the general public. Greenhouse structures (size, specification) vary with the topographic conditions, crop types, and irrigation technologies. Greenhouse facilities are usually built on level terraces or flat plateaus. They are supported by metal beams and arches, covered by plastic films along with automated temperature control devices. Their sizes are limited by the slope aspect, width and length of the terraces. Usually, the area space of is about 80 m long, 10 m wide. The cropping area is about 76 m long, 9 m wide, and a total area of 684 m².

4.2. Irrigation Requirement
According to the above mentioned cropping models and simulated irrigation schemes, all five (5) cropping models require between 3150 – 3960 mm irrigation amounts. Each greenhouse with a 684 m² cropping area needs about 215.5 – 270.9 m³ of irrigation water per year. The simulated irrigation requirement for greenhouse vegetable cropping system in Anding District is listed in Table 3.

Table 3. Irrigation requirement for greenhouse vegetable cropping system in Anding District.

| No. | Cropping model | Irrigation amount (mm) | Irrigation requirement for each greenhouse (m³) |
|------|----------------|------------------------|-----------------------------------------------|
| 1    | Eggplant + FWGLV* | 3150                   | 215.5                                        |
| 2    | Pepper + FWGLV    | 3690                   | 252.4                                        |
| 3    | Tomato + FWGLV    | 3960                   | 270.9                                        |
| 4    | Cucumber + FWGLV  | 3960                   | 270.9                                        |
| 5    | Pumpkin + FWGLV   | 3285                   | 224.7                                        |

*FWGLV = Fall-winter green-leaf vegetable
5. Plastic Rooftop Rainwater Harvesting

5.1. Designed Annual Rainfall Distribution
Based on the past 58 (1958 - 2015) years of rainfall records, the computed 20%, 50% and 75% frequency of occurrence of annual rainfall amount is about 461.7 mm, 389.6 mm and 341.0 mm, respectively. According to typical year selection, year 1984, 1975, and 2011 represents the 20% “wet”, 50% “normal”, and 75% “moderately dry” rainfall years, respectively. The annual distribution of monthly rainfall amount for various reliability percentage or typical rainfall year is listed in Table 4.

Table 4. The annual distribution of monthly rainfall amount at various reliability percentage

| Reliability (%) | Typical year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Total |
|-----------------|-------------|---|---|---|---|---|---|---|---|---|----|----|----|------|
| 20              | 1984        | 2.8| 1.6| 8.8|22.2|68.2|74.5|91.5|119.2|50.8|19.7|0.0 |2.4 |461.7 |
| 50              | 1975        | 1.9| 2.9| 3.7|21.3|52.5|63.7|75.5|91.4 |47.1|18.3|7.9 |3.4 |389.6 |
| 75              | 2011        | 4.7| 1.9| 8.6|14.4|44.3|46.3|64.7|76.0 |42.7|17.9|17.9|1.6 |341.0 |

5.2. Efficiency of Various Collection Materials
Collection efficiency, similar to runoff coefficient, depends on the conditions of collection surface and rainfall. This efficiency varies with the total amount of rainfall. Annual collection efficiency for plastic films often exceed 75 – 80%. As such, collection efficiency may reach as high as 95% with heavy rainfall events and plastic films. Concrete surface has a lower efficiency of about 70 – 75%, followed by asphalt felt with about 70%. Collection efficiency with different rainfall amount and collection materials is listed in Table 5 [3] [4].

Table 5. Collection efficiency with with different rainfall amount and collection materials

| Item             | Rainfall amount (mm) |
|------------------|----------------------|
|                  | 250      | 300     | 350    | 400     | 450     | 500     |
| Plastic film     | 70       | 72      | 74     | 76      | 79      | 82      |
| Concrete surface | 68       | 69      | 71     | 73      | 75      | 78      |
| Asphalt felt     | 65       | 68      | 70     | 72      | 73      | 74      |

5.3. Rainwater Harvesting Estimation
Plastic rooftop in greenhouses may provide beneficial effects in both irrigation and rainwater collection. Rainwater is collected with cement trough of 20 cm wide and 15 – 20 cm deep constructed all around the greenhouse. The amount of rainwater harvested may be estimated by the capacity of collection trough and plastic rooftop collection area, using the following equation:

\[ W_j = 10^{-3} P_p \cdot (S_m \cdot E_m + S_h \cdot E_h) \] (1)

Where
- \( W_j \) = collection volume of plastic rooftop greenhouse, m³
- \( P_p \) = rainfall amount with p frequency of occurrence, mm
- \( S_m \) = effective collection area of plastic rooftop, m²
- \( S_h \) = effective collection area of cement trough, m²
- \( E_m \) = collection efficiency of plastic film, %
- \( E_h \) = collection efficiency of cement trough, %

The estimated harvested rainfall using plastic rooftop is shown in Table 6 at different rainfall occurrence frequency. During wet years (p = 20%), the estimated rainwater collection should satisfy the irrigation requirement (Table 3) for all 5 cropping models. In normal years (p = 50%), irrigation requirement of models 1 (Eggplant + FWGLV), 2 (Pepper + FWGLV) and 5 (Pumpkin + FWGLV) may be satisfied. Models 3 (Tomato + FWGLV) and 4 (Cucumber + FWGLV) may not be satisfied. Water shortage amounts to about 15.0 m³. For moderate dry years (p = 75%), only model 1 irrigation requirement can be satisfied. The other models experience water shortage of about 6.5 – 52.7 m³. Therefore, additional supplemental water supply is needed. It can be provided by increasing collection area and collection amount to secure adequate irrigation water for vegetable crops in greenhouse.
Table 6. Estimated harvested rainfall amount using plastic rooftop at different rainfall occurrence

| Frequency of rainfall occurrence (%) | Rainwater collection amount (m³) |
|-------------------------------------|---------------------------------|
| 20                                  | 319.6                           |
| 50                                  | 255.9                           |
| 75                                  | 218.2                           |

5.4. Determination of Additional Collection Area

Fluctuation of rainfall amount between dry and wet years greatly affect irrigation water supply in greenhouse agriculture. Irrigation water supply solely depends on plastic rooftop harvesting is not sufficient during dry years. Other type of collection surfaces are needed to supplement water demand. To alleviate water shortage problems, transportation road surface and unused space between greenhouses may be utilized. Rainwater intercepted by transportation road may be diverted by road-side ditches (if space available) to increase harvested rainwater. Additional water harvested can be estimated, based on collection material efficiency, along with equation 2 [5].

\[
W_g = W_j + W_b
\]

Where,  
\[W_g = \text{total water supply of greenhouse rainwater harvesting system, m}^3\]  
\[W_j = 10^{-3} P_{75\%} \times S_b \times E_b\]  
\[P_{75\%} = \text{annual rainfall amount at } p = 75\% \text{ frequency, mm}\]  
\[W_b = \text{supplemental rainwater collection amount, m}^3\]  
\[S_b = \text{supplemental collection area, m}^2\]  
\[E_b = \text{supplemental collection material efficiency, } \%\]

The needed additional collection surface area may be determined by the water balance rationale. The study results are listed in Table 7.

Table 7. Additional collection surface area needed during moderate dry years (p = 75%)

| Model | Water shortage (m³) | Cement collection surface (m²) | Asphalt collection surface (m²) |
|-------|---------------------|-------------------------------|-------------------------------|
| 1     | NA*                 | NA                            | NA                            |
| 2     | 34.2                | 142.0                         | 144.0                         |
| 3     | 52.7                | 218.6                         | 221.8                         |
| 4     | 52.7                | 218.6                         | 221.8                         |
| 5     | 6.5                 | 26.9                          | 27.3                          |

*NA – not applicable (no shortage)

Note: Only one type (cement or asphalt) is used to satisfy requirement

According to results of Table 7, during moderate dry years, additional collection area between 26.9 – 218.6 m² cement surfaces or 27.3 – 221.8 m² asphalt surfaces are needed to fulfill irrigation reliability requirement.

6. Determination of Rainwater Storage Capacity

6.1. Regulatory water requirement

Irrigation requirement for all vegetable growing stages should be met with the plastic rooftop rainwater harvesting system in addition to the supplemental collection surface areas estimated during the moderate dry years. However, due to the uneven distribution of rainfall for different seasons and months, water supply for some time period may not be sufficient and balanced. Therefore, adequate engineering measure needs to regulate water supply and to store surplus water during wet periods to provide water during lean periods. This way, sufficient water may then be secured for the entire cropping cycle.

The storage capacity for each time period (month) is determined based on the water balance considerations on supply and demand, and the regulatory irrigation water requirement. Comparing the
storage capacity required for each month, the maximum storage capacity may then be estimated. Table 8 lists the water balance computation for all five (5) cropping models under the moderate dry years (p = 75%).

Table 8. Water balance results in m$^3$ for all five (5) cropping models under moderate dry years (p = 75%)

| Model | Item   | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | Total |
|-------|--------|------|------|------|------|------|------|------|------|------|------|------|------|-------|
| 1     | Supply | 3.0  | 1.2  | 5.5  | 9.2  | 28.4 | 29.6 | 41.4 | 48.6 | 27.3 | 11.5 | 11.5 | 1.0  | 218.2 |
|       | Demand | 13.1 | 0.0  | 0.0  | 15.4 | 26.7 | 35.8 | 43.5 | 34.6 | 10.3 | 0.0  | 25.9 | 10.3 | 215.5 |
|       | Balance| -10.1| 1.2  | 5.5  | -6.2 | 1.7  | -6.1 | -2.1 | 14.0 | 17.1 | 11.5 | 14.5 | -9.2 | 2.8   |
|       | Storage| 6.0  | 7.3  | 12.8 | 6.6  | 8.3  | 2.1  | 0.0  | 14.0 | 31.1 | 39.8 | 25.3 | 16.1 |       |
|       | Supply | 3.5  | 1.4  | 6.4  | 10.7 | 32.8 | 34.3 | 47.9 | 56.3 | 31.6 | 13.2 | 13.2 | 1.2  | 252.4 |
|       | Demand | 13.1 | 0.0  | 0.0  | 20.5 | 36.2 | 41.8 | 45.3 | 38.6 | 20.8 | 0.0  | 25.9 | 10.3 | 252.4 |
|       | Balance| -9.6 | 1.4  | 6.4  | -9.9 | -3.4 | -7.5 | 2.6  | 17.7 | 10.8 | 13.2 | -12.7 | -9.1 | 0.0    |
|       | Storage| 13.0 | 14.4 | 20.8 | 10.9 | 7.5  | 0.0  | 2.6  | 20.3 | 31.1 | 44.3 | 31.7 | 22.6 |       |
|       | Supply | 3.7  | 1.5  | 6.8  | 11.4 | 35.2 | 36.8 | 51.4 | 60.4 | 33.9 | 44.2 | 44.2 | 1.3  | 270.9 |
|       | Demand | 13.1 | 0.0  | 0.0  | 21.9 | 37.4 | 44.1 | 53.6 | 41.6 | 23.1 | 0.0  | 25.9 | 10.3 | 270.9 |
|       | Balance| -9.3 | 1.5  | 6.8  | -10.5| -2.2 | -7.3 | -2.2 | 18.8 | 10.8 | 14.2 | -11.7 | -9.0 | 0.0    |
|       | Storage| 13.8 | 15.4 | 22.2 | 11.7 | 9.4  | 2.2  | 0.0  | 18.8 | 29.6 | 43.9 | 32.2 | 23.2 |       |
|       | Supply | 3.7  | 1.5  | 6.8  | 11.4 | 35.2 | 36.8 | 51.4 | 60.4 | 33.9 | 44.2 | 44.2 | 1.3  | 270.9 |
|       | Demand | 13.1 | 0.0  | 0.0  | 21.9 | 37.4 | 44.1 | 53.6 | 41.6 | 23.1 | 0.0  | 25.9 | 10.3 | 270.9 |
|       | Balance| -9.3 | 1.5  | 6.8  | -10.5| -2.2 | -7.3 | -2.2 | 18.8 | 10.8 | 14.2 | -11.7 | -9.0 | 0.0    |
|       | Storage| 13.8 | 15.4 | 22.2 | 11.7 | 9.4  | 2.2  | 0.0  | 18.8 | 29.6 | 43.9 | 32.2 | 23.2 |       |
|       | Supply | 3.1  | 1.3  | 5.7  | 9.5  | 29.2 | 30.5 | 42.6 | 50.1 | 28.1 | 11.8 | 11.8 | 1.1  | 224.7 |
|       | Demand | 13.1 | 0.0  | 0.0  | 15.4 | 28.7 | 33.7 | 47.8 | 39.6 | 10.3 | 0.0  | 25.9 | 10.3 | 224.7 |
|       | Balance| -10.0| 1.3  | 5.7  | -5.9 | 0.5  | -3.2 | -5.1 | 10.5 | 17.9 | 11.8 | -14.1 | -9.2 | 0.0    |
|       | Storage| 6.8  | 8.1  | 13.8 | 7.9  | 8.3  | 5.1  | 0.0  | 10.5 | 28.4 | 40.1 | 26.0 | 16.8 |       |

*Maximum storage amount = system storage capacity

6.2. Determination of System Storage Capacity
The storage capacity of the rainwater harvesting system is determined by the annual rainwater supply, irrigation requirement and the water regulatory estimation. As shown in Table 8, the system storage capacity varies between 39.8 – 43.9 m$^3$ for different cropping models under the designed irrigation schemes. Material usually used to construct the rainwater storage devices along with greenhouse facilities are mainly cement covered cellar with capacity between 15 – 30 m$^3$ or plastic coated impervious ponds with capacity between 20 – 30 m$^3$.

7. Conclusions
Increasing awareness of unconventional water resource utilization is more obvious nowadays along with the aggregation of global water crisis and the emerging water conflicts within regions. Rainwater harvesting, as one of the unconventional water sources, is becoming more important in social economic development and eco-environment maintenance in water scarce arid regions. The self-sustaining greenhouse plastic rooftop rainwater harvesting system may provide strong support for agricultural production in greenhouses and high efficient rainwater resource utilization in water deficit arid regions.

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