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Water Harvesting Induced by Reduction of Both Evaporation and Deep Percolation of Water under Some Growing Crops

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Abstract

In arid and semi-arid regions where precipitation is low or infrequent during the dry season, it is necessary to store a maximum amount of rainwater during the wet season for use during the dry season in the agriculture sector. Rainfall in the northern section of Saudi Arabia ranges from 100 to 200 mm. The shortage of rainfall, the high soil water evaporation and the deep-water percolation are the main problems that face the agriculture in the area under study. So, this study aims to evaluate a new technique of water harvesting depending upon reducing both evaporation and deep percolation of water. Several field plots (3- m wide, 5-m length, and 1 m- apart each) in the Agriculture and Veterinary Faculty Farm, Qassim University, were selected to carry out this study. A big metal cylinder was designed to dig conical pits (0.10-m depth and 0.10-m inside diameter) in the soil surface. These pits were means for collecting the rainfall or the sprinkler irrigation water. The pits were 0.30 m apart. A single plant of faba bean (Vicia faba, L) was planted nearby the pits on October 10, 2003 (winter season). Similarly, corn (Zea mays, L) and green bean (Phaseolus vulgaris, L) plants were sown on April 6, 2004 (summer season). Five treatments were used for rainfall harvesting including flat soil surface (control), empty conical pits, conical pits filled with fresh grass residues, conical pits filled with gravels and conical pits covered after plant emergence by drilled black plastic (winter season) or white plastic (summer season) sheet. Sprinkler irrigation system was used to simulate the rainfall when it was limited. Three replications were assigned for each treatment. The growth and yield parameters were monitored during the growing season that lasted on March 9, 2004 (winter season) and on July 20, 2004 (summer season).

The growth rate of faba bean (Vicia faba, L) for the plastic treatment was 9.5 mm/day while it was 5.9 mm/day for either the flat or grass residue treatment. The yield of faba bean (Vicia faba, L) decreased in the order of plastic> gravel> grass> pit> flat treatments. The fresh weight of green bean (Phaseolus vulgaris, L) showed a decrease in the order of gravel>plastic>pit>grass>flat treatments. In the corn (Zea mays, L) experiment, all treatments gave greater yield than that of the flat surface treatment (control). The results of this study validated that the soil surface management positively influences the crop yield and water conservation. Therefore, by using the designed machine, it can be seen the enhance of the soil water storage *in situ* leading to a great crop yield.

<u>Keywords</u>

Rainfall; sprinkler irrigation; water harvesting; new machine; evaporation; deep-percolation; mulch; water conservation; growth parameters; corn (Zea mays, L); faba bean (Vicia faba, L); green bean (Phaseolus vulgaris, L).

Introduction

Rainfall in the kingdom of Saudi Arabia takes place primarily during winter and spring. Rainfall of 100.0 to 200.0 mm occurs in an area extending from north of Riyadh (Capital of Saudi Arabia) to the vicinity of Hail (Ministry of Agriculture and Water, 1984). Water conservation is a mandatory goal in arid and semi-arid regions such as the Kingdom of Saudi Arabia. Water resources can be conserved through agronomic and engineering approaches (Sivanappan, 1997). The agronomic methods of water conservation include contour farming, deep tillage, planting on furrows, mulching, soil compaction and rainfall harvesting.

Water harvesting is the capture, diversion, and storage of rainwater for agriculture and other uses. Several methods have been practiced for the rainwater harvesting. One of these methods that are frequently used in the arid and semi-arid regions is the storage of rainwater *in situ.* For increasing the benefits of the rainfall, enhancement of the soil water storage, reduction of the water evaporation from a soil surface and reduction of the deep-water percolation are essential. Furrows may be used as an *in situ* mean of storing the harvested rainwater (International Environmental Technology Center, 1997). They are built before or after planting to store water for the plant use. In this method of rainfall storage, flattened trenches are used between crop rows to store water. Furrows may have mud dams or barriers every 2.0 to 3.0 m along each row in order to retain water for long time periods and to avoid excessive surface runoff and erosion. Raised beds may also be used to trap water in the furrows, or uncultivated areas may be left between rows of 1.0 m apart to assist in capturing the rainwater falling on land surface between furrows. Hulugalle et al. (1990) reported that sorghum grain yield increased using tied ridges, primarily due to increases in the soil water content during the flowering stage. Another technique for water harvesting is using pits of approximately 0.25 m -diameter and 0.20 m –depth **(**Malley et al., 2001; Kaboré and Reij, 2003). These pits (zaï as it is called in Burkina Faso) are sometimes filled with manure to provide the growing plants with both water and nutrients. However, they have some disadvantages as: a) their high labor requirements for digging (about 300 man-hours/ha), and b) their impossible mechanization **(**Kaboré and Reij ,2003).

Mulching the soil surface is another mean for suppressing water losses by evaporation. Most of water evaporation occurs, when the soil is wet, within a few days after rain or irrigation. Hillel (1980) reported that the rate of water evaporation during the early stage of irrigation or rainfall is limited by the external meteorological conditions (i.e. radiation, wind, air humidity, etc.) and by the soil surface conditions (i.e., the presence of mulch or aggregation of soil particles). When the soil surface is more often wet, as in the case of the sprinkler irrigation or the rainfall, the evaporation rate increases. Crop canopies also play a role in reducing the evaporation through shading the soil surface. The weed-free wheat stubble in west central Nebraska reduced the evaporation by 50.0 mm compared to a bare soil left from the wheat harvest in July until the row crop planting in the following May. These water savings can contribute to yield increases up to 10 bushels of corn (Zea mays, L) per acre. Surface mulches have been used to improve the soil water retention, lower the soil temperature, and reduce the wind velocity at the soil surface of arid lands (Kay, 1978; Jalota and Prihar, 1998). They can also improve the water penetration by impeding runoff, protecting the soil from the raindrop splash, and reducing the soil crusting (Munshower, 1994). Vertical mulches pushed or crimped into the ground can funnel the precipitation to substrate soils (Bainbridge, 1996). An early demonstration plot at the mesquite mounds site showed much improved survival with early bark mulch, and similar results have been found in other arid sites (Zink and Allen, 1995).

The compaction of the soil surface can also be a mean for water conservation. In humid regions, Ressler et al. (1997) developed a new technique for application of nitrogen fertilizers. The technique, which is called localized compaction and doming (LCD), includes smearing the macropores below the nitrogen slot and forming a compacted layer over the slot. This technique reduces the water and nitrogen movement downward simultaneously.

According to the reviewed literature, no attempts have been made to combine water harvesting, suppressing water evaporation and reducing the deep-water percolation as means of water conservation. Therefore, this study aims to test a new technique of water harvesting which depends upon accumulating water *in situ* and suppressing both soil water evaporation and deep percolation simultaneously. The proposed technique was evaluated by measuring the yields of some growing crops (faba bean (Vicia faba, L), green bean (Phaseolus vulgaris, L), and corn (Zea mays, L)).

Materials and Methods

A proposed technique of water harvesting depending upon the reduction of the evaporation and the deep-percolation of water under growing some field crops was evaluated on the farm of the Faculty of Agriculture and Veterinary, Qassim University. A water harvesting machine was designed, a sprinkler irrigation system was set up and field experiments were conducted to achieve this study.

I. A Water Harvesting Machine

To maximize the water use of the rainfall that was simulated by the sprinkler irrigation, a machine was designed for the compaction of soil *in situ* (Figure 1). This machine could reduce the deep-percolation of water, especially in the soils of high water permeability. The machine has 2.4 m in length and 0.5m in diameter. It is made of steel and weighs 500 kg. It costs about 11,000 SR (approximately 4,000 US $). The machine is drawn by a tractor to perform conical pits of 0.30-m apart. Each conical pit has a height and a diameter of 0.10 m. Eight rows of conical pits can be achieved using the machine. Figure (2) shows some conical pits that were made using the machine in a sandy loam soil.

Fig. 1: A designed machine for making pits in the soil surface.

Fig. 2: Pits achieved using the designed machine.

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II. A Sprinkler Irrigation System

Since the rain is infrequent in the Qassim region, a sprinkler irrigation system was designed to simulate the rainfall for watering an area of 1000 m^2. The system included seven lateral lines of 5-m apart. Each line had four sprinklers of 5-m apart.

III. Field Experiments

a. Faba bean (Vicia faba, L) (winter season)

A field experiment was conducted on an area of 1000 m^2 in the Agriculture and Veterinary Faculty Farm, Qassim University, Qassim, Saudi Arabia to evaluate a technique of water harvesting under growing faba bean (Vicia faba, L). The particle-size distribution of the soil of the studied area, as described by Gee and Bander (1986), had from 84 to 90.8 % sand, from 1.2 to 4.6 % silt, and from 4.6 to 14.8 % clay. The area was divided into plots of 3-m width, 5-m length and 1-m apart. The area was irrigated before performing the conical pits. During augmenting the pits, their circumference and bottom were compacted to reduce the deep-water percolation throughout the pits. To suppress the water evaporation from the conical pits, five different treatments of mulching were used. The flat soil surface (control) and empty conical pits were considered as the first and second treatments, respectively. In the third treatment, the pits were filled using fresh grass residue, while the pits in the fourth one were filled by gravels of a diameter ranged from 5.0 to 20.0 mm. In the fifth treatment, the conical pits were dug, then faba bean (Vicia faba, L) seeds were sown on their edges and the whole plot was covered using a drilled black plastic sheet, after two leaves/plant were seen, to allow the water to accumulate beneath it in the conical pits. In the plastic treatments, most of the dropped water from sprinkler irrigation or rainfall, on the surface of the sheet can accumulate beneath it. So, the five treatments will be referred as: flat, pit, grass, gravels and plastic. Faba bean (Vicia faba, L) seeds were sown on the edge of the conical pits manually on October 20, 2003 under the five treatments. Three plots were assigned as replications for each treatment. The experimental units were distributed as a randomized complete block design (RCBD) (Steel and Torrie, 2000). The plastic treatments started just after the emergence of the plants of two leaves. The plants were fertilized using urea (46%N) at a level of 5 g/plant on the December 3, 2003. For monitoring the soil matric potential under growing faba bean (Vicia faba, L) conditions, tensiometres were inserted in different locations at depth of 0.15 m in the flat plots. The irrigation water was added using the sprinkler system when the soil matric potential reached –15 kPa. Three destructive soil samples as replications were collected from each plot to measure the soil water content (9 samples for each treatment). The samples were randomly collected at a depth of 0.10 m on February 10, 2004 (112 days after planting). The soil water content was determined in the soil samples gravimetrically by drying them at 105 ^oC. The growth and yield parameters were monitored during the growing season. The growth parameters included the shoot height, fresh weight, moisture content and dry matter. The moisture content of the vegetative parts was determined by drying the plant samples at 65 ^oC. These parameters were recorded on December 19, 2003, January 18, 2004 and February 23, 2004 at corresponding time periods of 60, 90, and 125 days from sowing. The yield parameters were collected on March 10, 2004 and included the number of pods and their weights. Least significant differences (LSD) at a 5% level were used to test the differences among the treatments as described by Steel and Torrie (2000).

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b. Corn (Zea mays, L) and green bean (Phaseolus vulgaris, L) (summer season)

Two other field experiments were performed on other areas (1000 m^2) on the same farm on April 6, 2004 to evaluate the same technique of water harvesting using corn (Zea mays, L) and green bean (Phaseolus vulgaris, L) plants. The treatments that were used in these experiments were similar to those of the previous ones of faba bean (Vicia faba, L). However, in this experiment, white plastic sheets were used instead of the black ones for the plastic treatment. Irrigating the plants using the sprinkler irrigation system was done twice a day for 10 minutes each time. The plants were fertilized using 2 doses of urea at a level of 5 g/plant for each dose on May 5 and June 6, 2004. The length of the green bean (Phaseolus vulgaris, L) plants was recorded on May 25, 2004. Some growth parameters were obtained on June 5, 2004 for the green bean (Phaseolus vulgaris, L)s. The length of corn (Zea mays, L) shoots was recorded on May 25, June 5, June 20, and July 20, 2004.

Results and Discussion

a. Faba bean (Vicia faba, L) Experiment:

Figure (3) shows the effect of the growth time period on the shoot length of faba bean (Vicia faba, L) plants under different mulch treatments. It is obvious that the shoot length increased as the growth time period (plant age) increased. The plastic treatment possessed the tallest shoots while the flat soil surface (the control) gave the shortest ones. There are two reasons for the superiority of the plastic treatment over the others. First, the plastic sheets enhance the soil moisture storage that can be absorbed by plants. In addition, increasing the water storage reduces the leaching of plant nutrients by mass flow (Ressler et al., 1998). Therefore, increasing the water storage and reducing the nutrient loss lead to better faba bean (Vicia faba, L) growth. Second, black plastic sheets absorb solar heat during the day time causing the soil temperature to increase which is favourable for the growing plants. Mahmoud (1996) reported similar findings. He showed that mulching the soil with single and double layers of polyethylene sheets for 10 weeks resulted in an increase in the soil temperature at depths of 0.10 and 0.20 m, compared to the unmulched soil surface. The increase in the soil temperature results in uptake increases soil water and nutrients by plants. On the other hand, the low soil temperature retards the uptake of water and nutrients by plants (Tisdale and Nelson, 1975). A first-order polynomial was regressed using the collected data of shoot length. The coefficients of determination (R^2) for flat, pit, plastic, gravel and grass treatments were 0.99, 0.96, 0.97, 0.89, and 0.99, respectively. It is clear that the polynomial described quite well the shoot length as a function of growth time period for most treatments. The slope of the polynomial represents the changes in the shoot length as a function of the growth time period. These changes decreased in the order of plastic>pit>gravel>flat>grass. They varied from 5.9 mm/day for the grass treatment to 9.6 mm/day for the plastic one.

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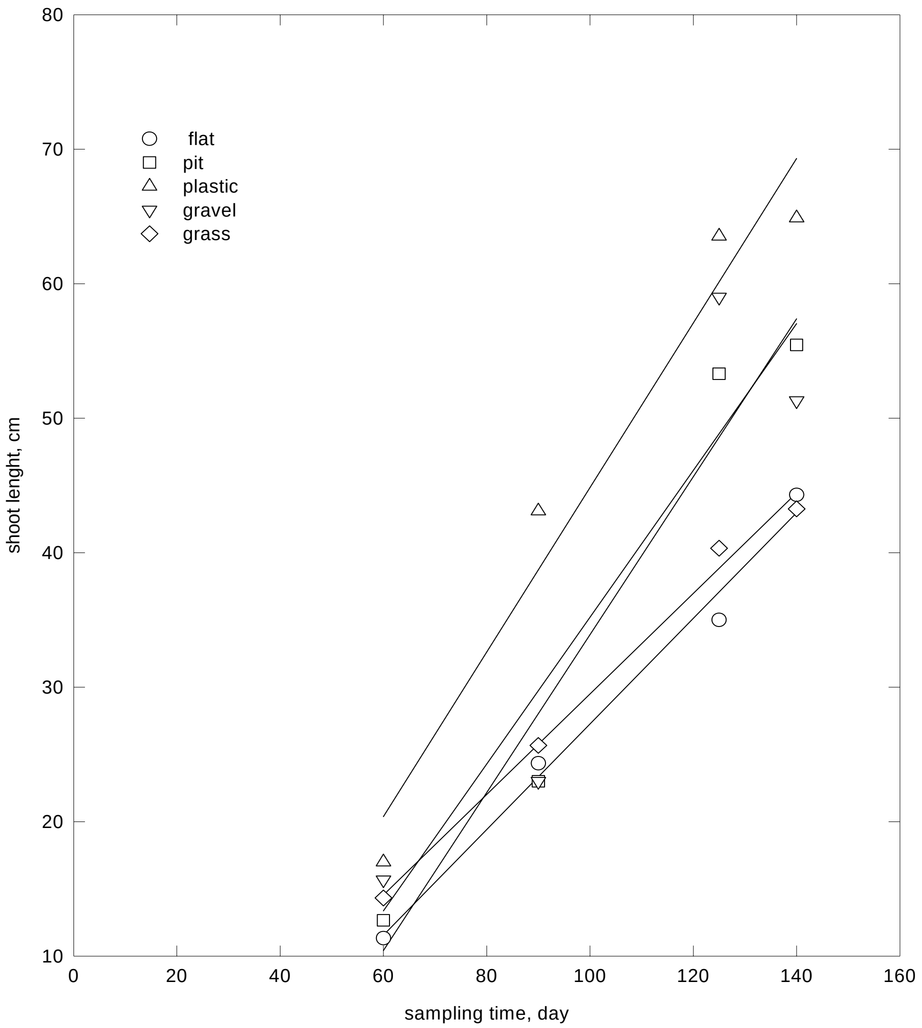

Fig. 3: Effect of the growth time on the shoot length of faba bean. The symbols are measured values and the solid lines are calculated using a first order polynomial

The fresh weight of faba bean (Vicia faba, L) shoots is illustrated in Figure 4 as a function of growth time period under different treatments of mulching. The fresh weight increased until 125 days from sowing for all treatments then it decreased with a further increase in the time. This trend indicates that the water content of plant shoots decreased after 125 days of sowing. The plastic treatment resulted in the greatest fresh weight while the flat soil surface gave the lowest one. These results are consistent with those of the shoot length that were discussed earlier.

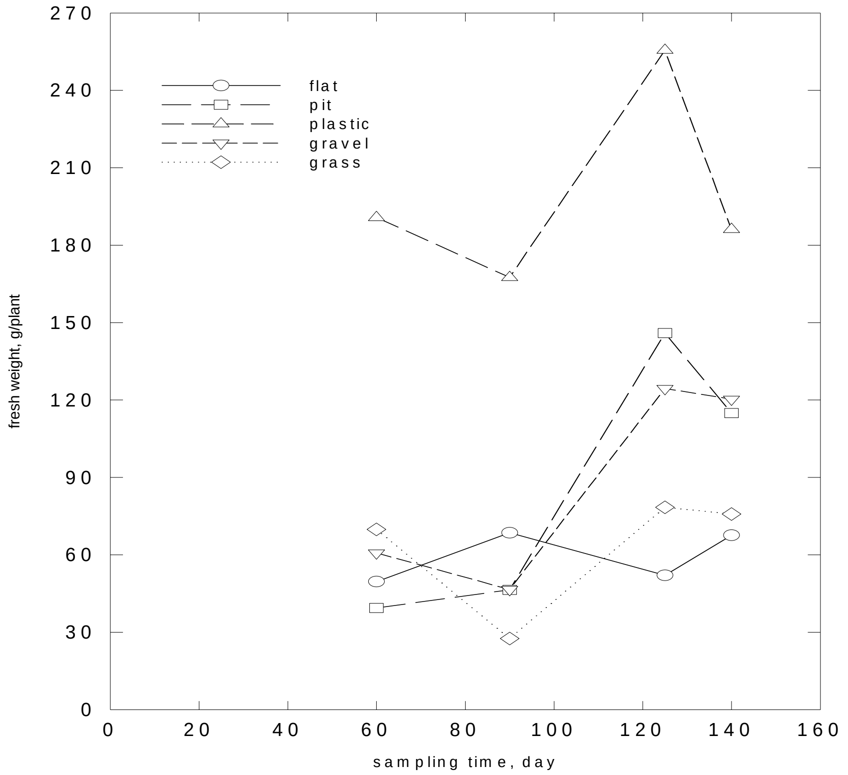

Fig. 4: Effect of the growth time on the shoot fresh weight of faba bean

The dry weight of faba bean (Vicia faba, L) shoots increased as the growth time increased from 60 to 125 days from planting for all treatments except the flat one (Figure 5). The plastic treatment had the greatest dry weight of faba bean (Vicia faba, L) shoots. The results of the shoot dry weight coincide with those of the shoot fresh weight.

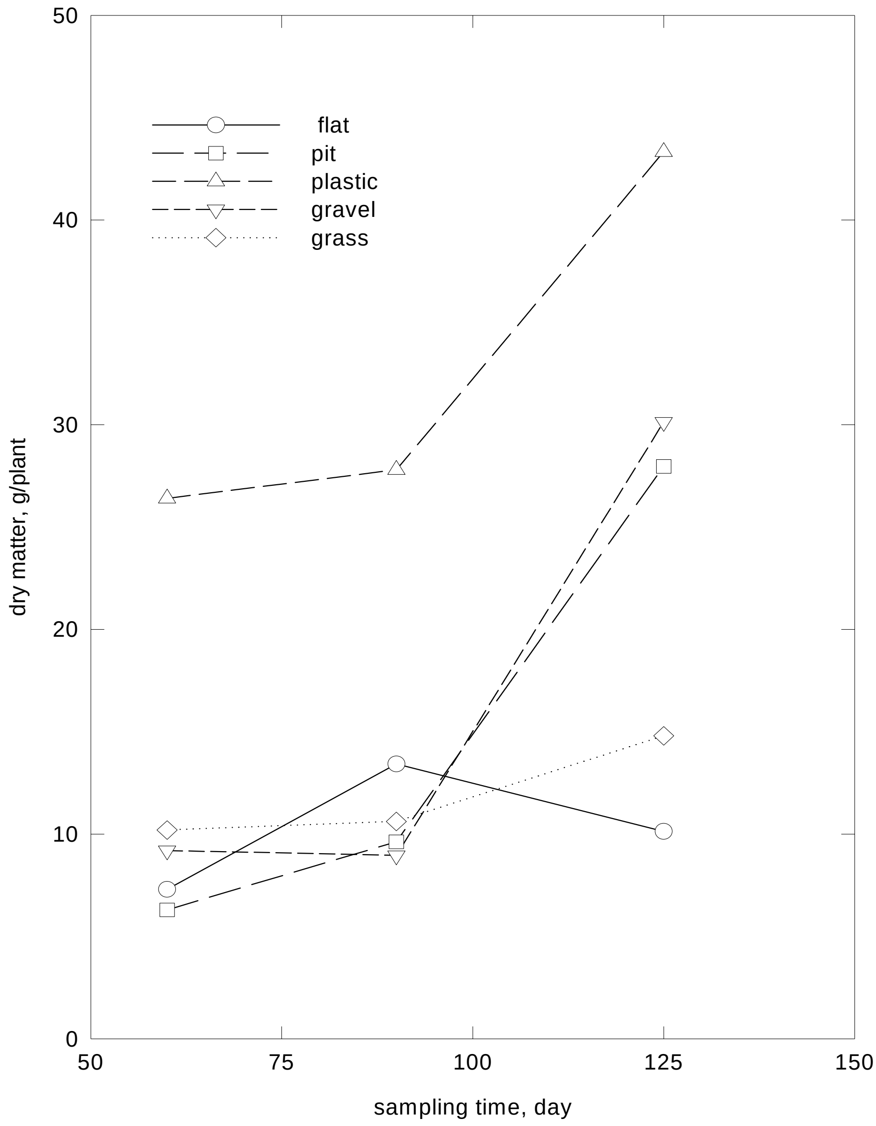

Fig.5: Effect of the growth time on the shoot dry weight of faba bean.

Number of faba bean (Vicia faba, L) pods per plant and their weight after 140 days of planting are shown in Figures 6 and 7, respectively. The plastic treatment also gave the greatest number and weight of pods while the flat one had the lowest ones. The weight of pods decreased in the order of plastic> gravel> grass>pit>flat. These results agree with those the aforementioned about growth parameters.

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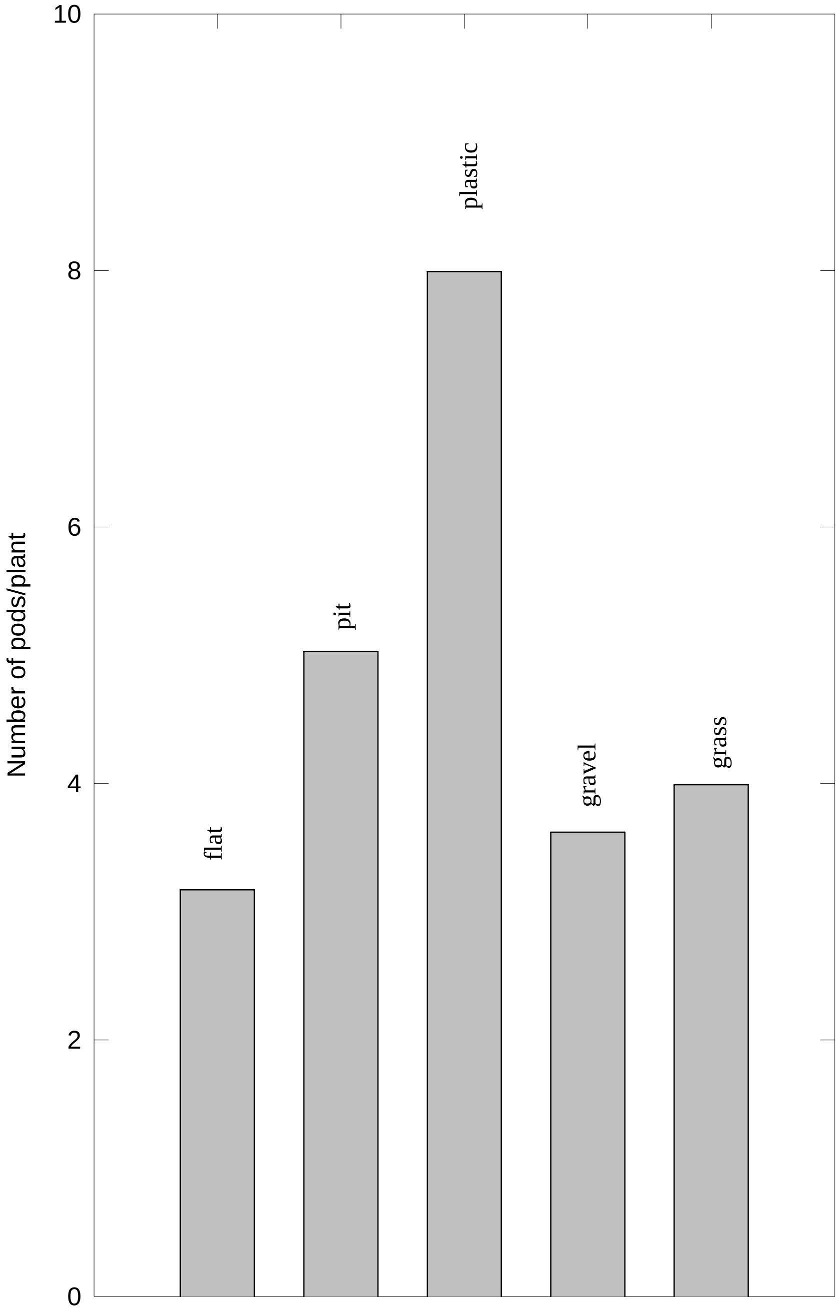

Fig.6: Number of pods per plant for faba bean under some soil mulch treatments.

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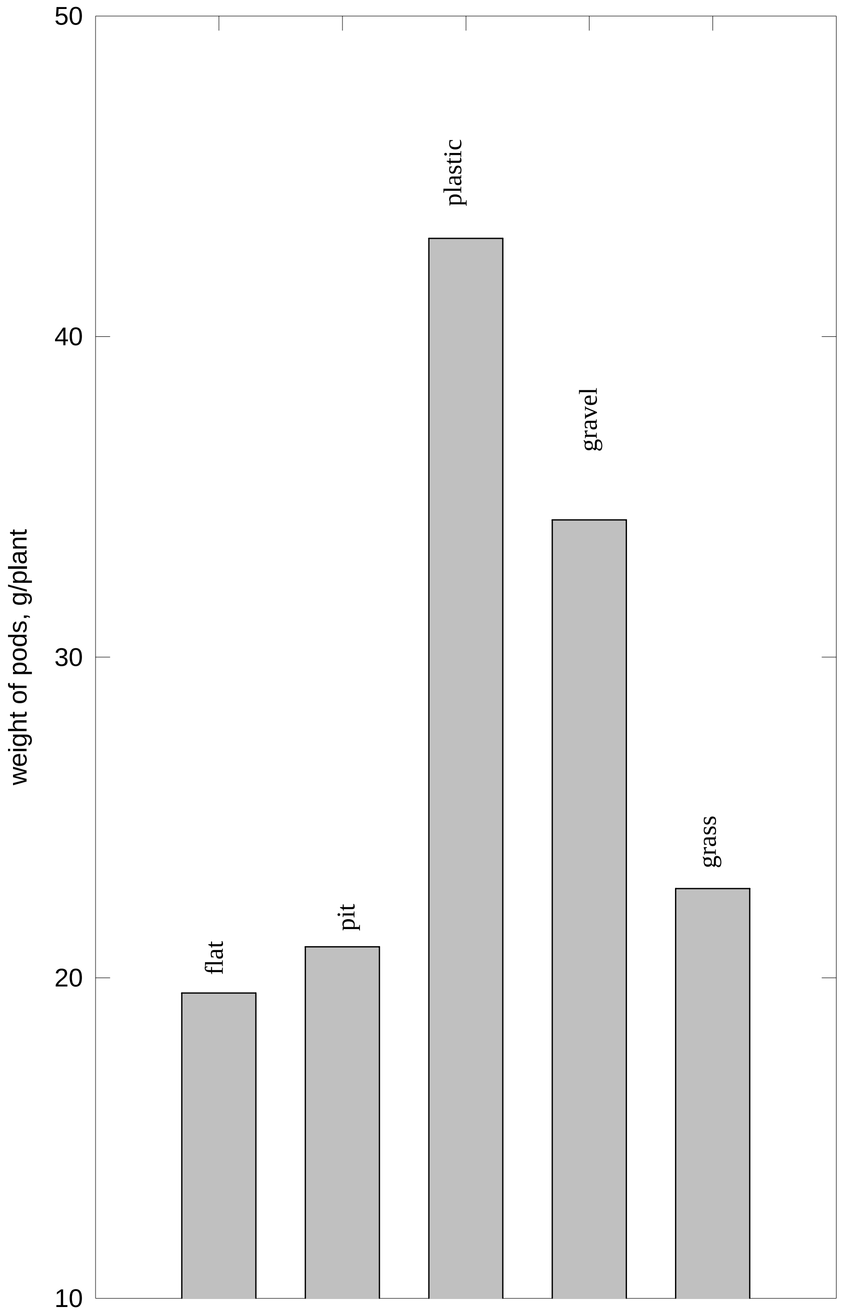

Fig. 7: Weight of pods per plant for faba bean under some soil mulch treatments.

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The soil moisture content was measured in the upper 0.10 m- layer under the studied mulch treatments after 112 days of planting. The flat, pit, plastic, gravel, and grass treatments resulted in soil moisture contents of 0.0527, 0.0744, 0.0747, 0.0385 and 0.0504 g/g, respectively. The moisture content had the greatest values under the plastic and pit treatments compared to the others. The highest moisture content using the plastic treatment is attributed to the water evaporation suppression from the soil. These results are expected since the water losses are mainly via both deep percolation and plant transpiration under the plastic treatment.

b. Green bean (Phaseolus vulgaris, L) and Corn (Zea mays, L) Experiment:

The fresh weight of green bean (Phaseolus vulgaris, L) shoots under the studied mulch treatments of the soil surface is illustrated in Table 1 and Figure (8). The flat soil surface gave the lowest fresh weight (9.1 g/plant) while the gravel treatment gave the highest one (18.8 g/plant). The gravel treatment gave fresh weight twice as the flat one. It enhanced the soil to store water and plant nutrients resulting in greater growth of green bean (Phaseolus vulgaris, L) shoots. The difference in the fresh weight between the gravel treatment and the grass residue, plastic, or pit one was small. Therefore, all treatments showed increases in the fresh weight of shoots. This means that all studied mulch treatments help storing soil water and nutrients compared to the flat soil surface (control). The results of green bean (Phaseolus vulgaris, L) growth parameters are in agreements with those aforementioned for faba bean (Vicia faba, L). The flat soil surface also gave the lowest value of shoot dry weight. On the other hand, the plastic treatment possessed the greatest dry weight of green bean (Phaseolus vulgaris, L) shoots (Table 1 and Figure 9).

It is also clear from Table 1 that the plastic treatment of the soil surface possessed the lowest water content of green bean (Phaseolus vulgaris, L) shoots among all mulch treatments. The difference in the water content of green bean (Phaseolus vulgaris, L) shoots between the plastic treatment and the gravel or the grass residue one was significant. The shoot length of green bean (Phaseolus vulgaris, L) plants varied from 0.17 to 0.20 m. The shortest shoots were obtained under flat soil surface treatment while the tallest ones were found under the gravel treatment. The differences in the shoot length of green bean (Phaseolus vulgaris, L) among the studied treatments were not significant.

Table 1 also shows the effect of mulch treatments of the soil surface on the weight and number of ears per corn (Zea mays, L) plant. The flat soil surface treatment possessed the lowest weight of corn (Zea mays, L) ears (164.6 g/ plant). The pit and plastic treatments gave the greatest weight of ears (258.1 and 253.7 g/plant, respectively). The differences in the weight of corn (Zea mays, L) ears among the treatments were not significant. The number of corn (Zea mays, L) ears ranged from 1.5 to 2.5 ears per plant. The flat soil surface and gravel treatments possessed the lowest number of ears while the plastic one had the highest ones. The difference in the ear number between the plastic treatment and the flat or the gravel one was significant. The higher corn (Zea mays, L) yield under plastic, gravel, pit, and grass treatments is attributed to the higher level of water storage and nutrients compared to that with the flat one (control). Similar findings were reported by Ressler et al. (1998) for the humid region. Ressler et al. (1997) developed a new technique for reducing nitrogen leaching and increasing water storage simultaneously. The technique included smearing the macropores below the nitrogen slot and forming a compacted layer over the slot.

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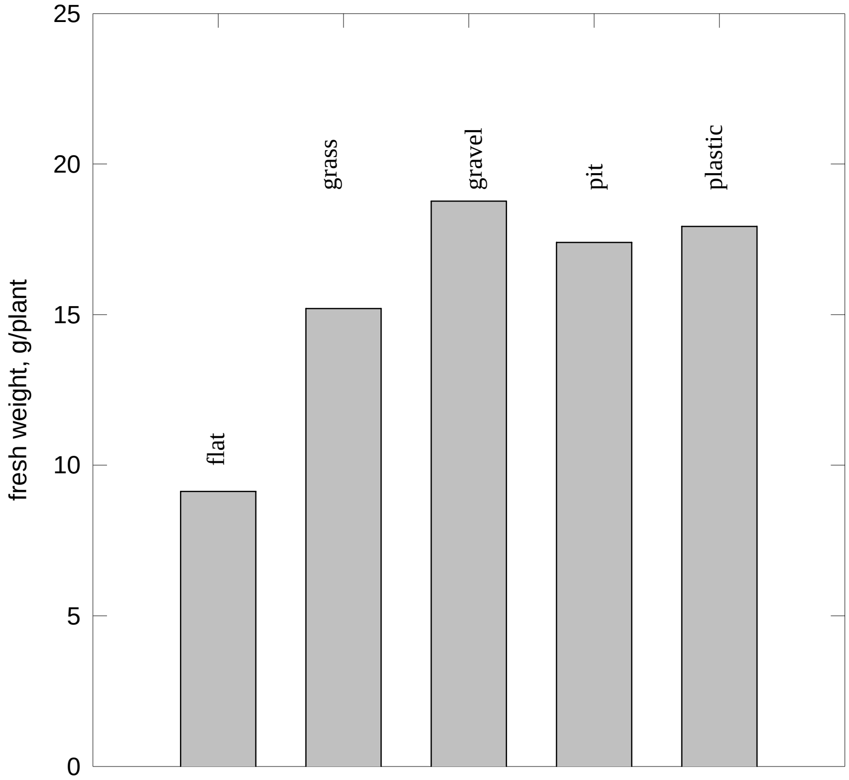

Fig. 8: Effect of some soil mulch treatments on the shoot fresh weight of green bean.

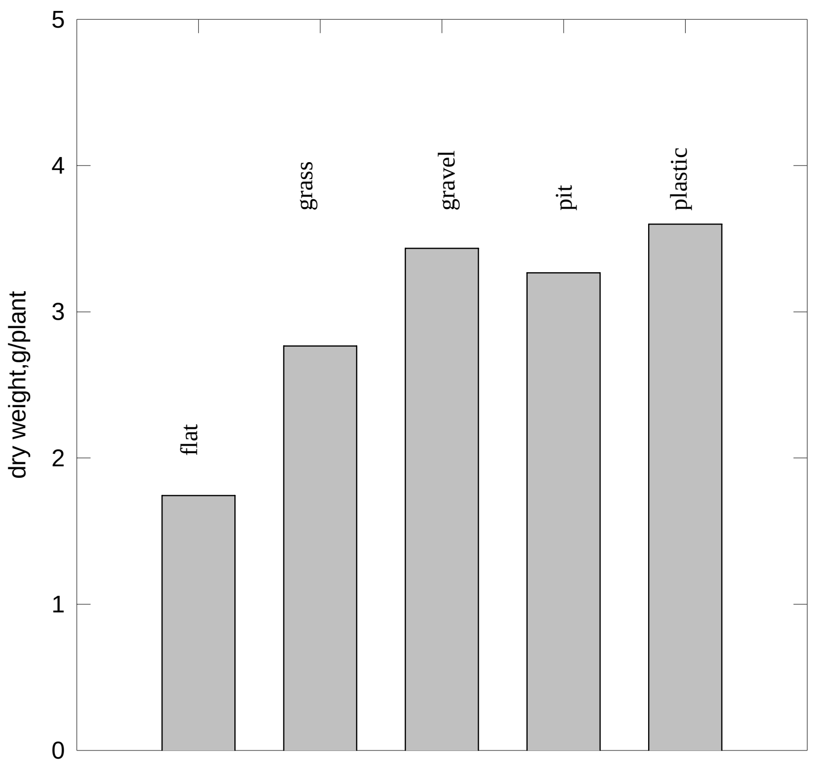

Fig. 9: Effect of some soil mulch treatments on the shoot dry weight of green bean.

Figure (10) shows the effect of the growth time on the shoot length of corn (Zea mays, L) under the studied treatments. The data represents a growth time period from 49 to 105 days of seedling. The shoot length increased as the time period increased. The conical pit, gravel, and plastic treatments gave the tallest shoots while the grass and flat ones possessed the shortest ones. The shoot length trend was consistent with that of other growth parameters of corn (Zea mays, L). A first-order polynomial was regressed with the collected data of the corn (Zea mays, L) shoot length. The coefficients of determination (R^2) for the flat, pit, plastic, gravels and grass treatments were 0.96, 0.96, 0.92, 0.87, and 0.78, respectively. The polynomial described reasonably well the corn (Zea mays, L) shoot length as a function of the growth time. The slope of the polynomial represents the changes in the corn (Zea mays, L) shoot length as a function of the growth time for the corresponding treatments. The change rates were 13.2, 8.2, 12.5, 13.2, and 12.1 mm/day for the flat, grass, gravel, pit and plastic treatments, respectively. The change rates coincided with shoot lengths because the rates were calculated for the last 56 days of the growth period. The change rates for the flat, plastic, gravel and pit treatments were almost similar. On other hand, the grass treatment possessed the lowest change rate among all treatments.

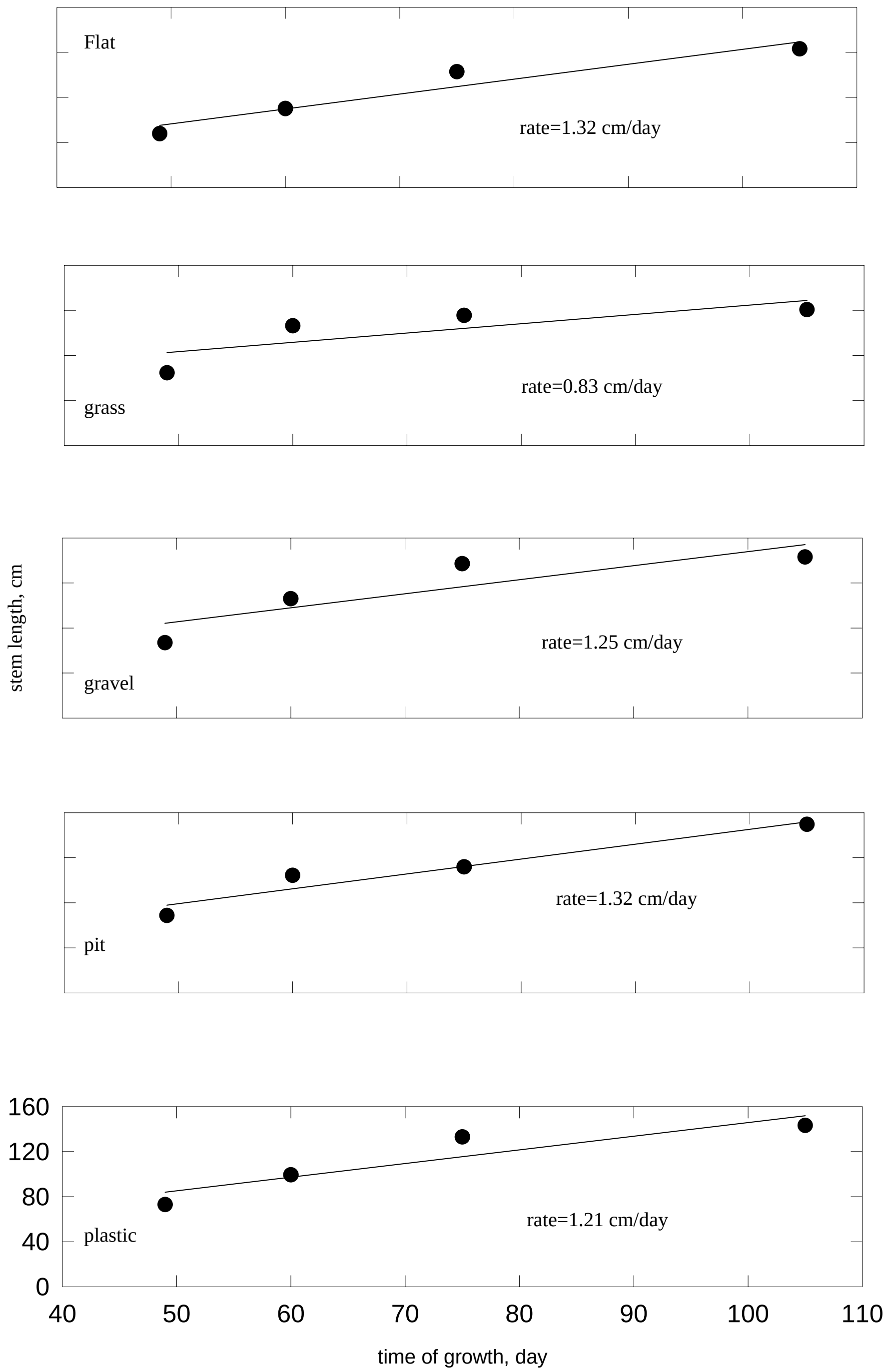

Fig. 10: Effect of some soil mulch treatments on the shoot growth rate of corn. The solid lines were calculated using a first order polynomial.

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Conclusions

The present study was directed toward increasing the agricultural water use efficiency of rain and sprinkler water. Increasing the water use efficiency was achieved by water harvesting, and reducing both water evaporation and deep-water percolation simultaneously. A new machine was designed for achieving conical pits of 0.10 m-depth and 0.10 m-diameter in the soil surface. To suppress the water evaporation from the soil surface, the conical pits were filled by the gravel or fresh grass residue or covered using a drilled plastic sheet. Besides these treatments, a flat soil plot (control) and conical empty pit plot were used as other two treatments. The drilled plastic sheet covered a whole plot that included conical pits and their adjacent soil surface. The combined effect of reducing the water loss from evaporation and deep-percolation was evaluated by growing three crops (corn (Zea mays, L), faba bean (Vicia faba, L) and green bean (Phaseolus vulgaris, L)) in two consecutive seasons. The machine increased the soil bulk density leading to reduction in soil hydraulic conductivity within the conical pit and resulting in a decrease in water deep-percolation. The plastic sheet treatment resulted in a great yield for the three grown crops in comparison with the flat soil surface (control) treatment. It is highly recommended to use the machine to save water under rainfall or sprinkler irrigation system with spaced-planted crops such as corn (Zea mays, L) or faba bean (Vicia faba, L). If some mulching materials are available for reducing water evaporation, the new machine will be used more effectively in enhancing the soil water storage.

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Tables

Table 1: Effect of certain mulch treatments of the soil surface on some growth parameters of corn and green bean.

Plant type	Parameter	Flat	Grass	Gravel	Pit	Plastic	$LSD_{(0.05)}$
Green beans	Water content, (g/g)	0.809	0.816	0.816	0.812	0.798	0.016
	Dry weight, (g/plant)	1.74	2.77	3.43	3.27	3.60	1.51
	Fresh weight, (g/plant)	9.13	15.2	18.8	17.4	17.9	8.3
	Length, (cm)	17.42	19.94	20.37	19.9	19.91	n.s.
Corn	Weight of ears, (g/plant)	164.6	210.4	176.7	258.1	253.7	n.s.
	Number of ears/plant	1.5	1.94	1.5	2.17	2.5	0.7