Effects of Furrow Mulching Materials on Soil Temperature, Crop Yield, and Water Use Efficiency in Ridge-Furrow Rainwater Harvesting Systems Postprint

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Abstract

To identify environmentally friendly furrow mulching materials for ridge-furrow rainwater harvesting in semi-arid regions, improve soil moisture and temperature conditions, and enhance rainfall resource use efficiency, a field experiment with completely randomized design was conducted using maize and sorghum as test crops and no furrow mulching as the control to investigate the effects of different furrow mulching methods (no mulching, liquid film mulching, straw mulching, and biodegradable plastic film mulching) on soil temperature, soil moisture, crop yield, water use efficiency, etc. The results showed that, compared with no mulching, liquid film and biodegradable plastic film mulching increased surface layer (0–25 cm) soil temperature in furrows planted with maize by 0.2 °C and 1.0 °C, respectively, and in furrows planted with sorghum by 0.2 °C and 1.1 °C, respectively, during the entire crop growth period; straw mulching decreased surface layer soil temperature in furrows planted with maize and sorghum by 1.1 °C and 1.3 °C, respectively; liquid film mulching, straw mulching, and biodegradable plastic film mulching increased 0–140 cm soil water storage by 0.4 mm, 21.5 mm, and 8.6 mm, respectively, for maize cultivation, and by 2.3 mm, 21.0 mm, and 10.9 mm, respectively, for sorghum cultivation. Liquid film and biodegradable plastic film mulching increased maize silage yield by 0.4% and 10.4%, grain yield by 1.6% and 11.3%, and aboveground biomass by 0.7% and 7.3%, respectively; sorghum silage yield by 0.2% and 10.9%, grain yield by 1.1% and 11.8%, and aboveground biomass by 1.6% and 9.4%, respectively; straw mulching decreased maize silage yield, grain yield, aboveground biomass, sorghum silage yield, grain yield, and aboveground biomass by 2.9%, 2.2%, 1.9%, 0.7%, 1.4%, and 1.0%, respectively. Liquid film mulching, straw mulching, and biodegradable plastic film mulching increased water use efficiency for maize cultivation by 0.9 kg · hm^{-2} · mm^{-1}, 0.5 kg · hm^{-2} · mm^{-1}, and 4.9 kg · hm^{-2} · mm^{-1}, respectively, and for sorghum cultivation by 0.3 kg · hm^{-2} · mm^{-1}, 0.4 kg · hm^{-2} · mm^{-1}, and 2.7 kg · hm^{-2} · mm^{-1}, respectively. Comprehensive analysis indicated that biodegradable plastic film is suitable as a furrow mulching material for ridge-furrow rainwater harvesting in the semi-arid Loess Plateau region.

Full Text

Effects of Furrow-Mulching Materials on Soil Temperature, Crop Yield and Water Use Efficiency in Ridge-Furrow Rainwater Harvesting Systems

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Abstract

To identify environmentally friendly furrow-mulching materials for ridge-furrow rainwater harvesting systems in semiarid regions, improve soil moisture and temperature conditions, and enhance rainfall resource utilization efficiency, a randomized complete field experiment was conducted using maize and sorghum as test crops. Four furrow-mulching treatments were compared: no mulching (control), liquid film mulching, straw mulching, and biodegradable film mulching. The results showed that compared with no mulching, liquid film and biodegradable film mulching increased topsoil (0–25 cm) temperature in maize furrows by 0.2 °C and 1.0 °C, respectively, and in sorghum furrows by 0.2 °C and 1.1 °C, respectively, during the entire growth period. In contrast, straw mulching decreased topsoil temperature by 1.1 °C for maize and 1.3 °C for sorghum. Soil water storage in the 0–140 cm layer increased by 0.4 mm, 21.5 mm, and 8.6 mm under liquid film, straw, and biodegradable film mulching, respectively, for maize, and by 2.3 mm, 21.0 mm, and 10.9 mm for sorghum. Biodegradable film mulching increased maize silage yield by 10.4%, grain yield by 11.3%, and aboveground biomass by 7.3%; corresponding increases for sorghum were 10.9%, 11.8%, and 9.4%. Liquid film mulching produced modest yield gains (0.4% and 0.2% for maize and sorghum silage, respectively), while straw mulching reduced yields across all metrics. Water use efficiency (WUE) increased most substantially under biodegradable film mulching, by 4.9 kg · hm^{-2} · mm^{-1} for maize and 2.7 kg · hm^{-2} · mm^{-1} for sorghum. Based on comprehensive analysis of crop performance, WUE, and environmental benefits, biodegradable film is recommended as the most suitable furrow-mulching material for ridge-furrow rainwater harvesting systems in the semiarid Loess Plateau region.

Keywords: Ridge-furrow rainwater harvesting; Furrow mulch material; Soil temperature; Soil moisture; Biodegradable film; Liquid film; Straw mulching; Maize; Sorghum

Introduction

The Dingxi region on the western Loess Plateau of Gansu Province suffers from severe water scarcity, high potential evapotranspiration, and insufficient accumulated temperature, making it one of China' s most impoverished areas. Located in the heart of China' s semiarid zone with a temperate continental monsoon climate, the region experiences high interannual rainfall variability and uneven seasonal distribution. Most precipitation events deliver less than 5 mm, which cannot be effectively utilized by crops. Shallow fertile soil layers, inadequate rainfall, and excessive land exploitation have led to sparse vegetation and soil degradation. Groundwater is deep and highly mineralized, rendering it unsuitable for drinking or irrigation. These fragile natural conditions result in low and unstable agricultural productivity, further exacerbated by extreme weather events including spring cold spells, drought, heavy rain, hail, and wind damage in recent years.

To improve agricultural productivity and ensure food security, local farmers have adopted various measures to combat drought, soil erosion, and spring cold, including terracing, silt dams, fish-scale pits, and ridge-furrow rainwater harvesting with mulching. This technology integrates conservation tillage and mulching practices, using ridges as rainwater collection zones and mulched or unmulched furrows as planting zones. Rainfall collected from ridges combines with direct precipitation in furrows, converting ineffective rainfall (<5 mm) into effective rainfall (>5 mm) and promoting infiltration, thereby improving rainfall utilization efficiency. Contour ridges intercept runoff, preventing water flow from high to low elevations, increasing water retention time in furrows, and reducing soil erosion. Al-Seekh and Mohammad reported that contour rainwater harvesting reduced runoff and sediment by 65-85% and 58-69%, respectively, significantly increasing soil water content and extending the growing period of natural vegetation, with more pronounced effects in arid and semiarid regions than in subhumid areas. Mulching materials in ridge-furrow systems reduce water and heat exchange between soil and atmosphere, improving soil moisture and temperature, promoting crop emergence and growth, and increasing yield and water use efficiency (WUE). Ren et al. found that ridge-furrow mulching increased topsoil (0-5 cm) temperature by 1.0-1.2 °C, maize grain yield by 11.2-82.8%, and WUE by 9.5-77.4% compared with flat planting without mulching. Li et al. reported that in subhumid regions, furrow mulching with conventional plastic film and biodegradable film increased topsoil temperature by 2.4 °C and 2.1 °C, respectively, maize grain yield by 35.2% and 34.7%, and WUE by 30.6%

and 30.2%, while straw mulching decreased topsoil temperature by 1.7 °C but still increased grain yield and WUE by 33.6% and 28.6%.

However, ridge-furrow rainwater harvesting reduces crop planting area and relative density. Li et al. noted that while plastic mulching significantly increased soil moisture and temperature during early growth, promoting root development, it also caused excessive early transpiration and vigorous growth. During later growth stages, particularly flowering, rising temperatures and decreasing rainfall limited the translocation of assimilates to reproductive organs, causing severe water stress and yield reduction. Most previous studies have used conventional plastic films, which are synthetic polyethylene or polyvinyl chloride polymers with stable molecular structures that resist biodegradation and are difficult to recycle. The widespread adoption of plastic mulching has created severe white pollution, with residual film fragments impeding mechanized tillage, reducing soil permeability and microbial activity, restricting water and nutrient movement, hindering root growth, degrading soil quality, reducing yields, and threatening livestock health, thereby limiting sustainable agricultural development. The emergence of environmentally friendly alternatives such as biodegradable, photodegradable, and photo-biodegradable films offers new opportunities for sustainable agriculture in semiarid regions. However, research on these materials in ridge-furrow systems remains limited, particularly in semiarid areas. This study investigated the effects of different furrow-mulching methods on soil temperature, water storage, silage yield, grain yield, and WUE to provide a theoretical basis for selecting efficient, water-conserving, and environmentally friendly mulching materials.

1.1 Study Area Overview

The experiment was conducted from March to October 2013 at the Dingxi Arid Meteorology and Ecological Environment Experimental Station of the Institute of Arid Meteorology, China Meteorological Administration (35°33 N, 104°35 E, elevation 1,896.7 m). Located in the western hilly region of the Loess Plateau, the site represents a semiarid rainfed agricultural area with a typical temperate continental monsoon climate. The mean annual temperature is 6.7 °C, with $ $0 °C accumulated temperature of 2,933.5 °C and $ 10°Caccumulatedtemperatureof2,239.1°C.Annualsunshinehoursaverage2,433h,whilemeanannualprecipi
1},23.59g·kg{-1},and11.76g · kg{-1},respectively.Availablenitrogen,phosphorus,andpotassiumaveraged54.3mg·
kg{-1},14.8mg · kg{-1},and245mg · kg^{-1}$, respectively.

1.2 Experimental Design

The experiment used ‘Shengdan 16’ maize and ‘Tianliang 3’ sorghum (*Sorghum bicolor*). The ridge-furrow rainwater harvesting system consisted of ridges 45 cm wide covered with biodegradable film as collection zones, and furrows 60 cm wide with different mulching materials as planting zones. Based on local experience, ridges were constructed along contours with a slope of approximately 40° and height of 20 cm, with a ridge length of 10 m (schematic diagram shown in [Figure

1: see original paper]). The experiment employed a randomized complete design with two crop types (maize and sorghum) and three furrow-mulching materials (liquid film, straw, and biodegradable film), plus a no-mulching control, totaling eight treatments (2 crops × 4 mulching methods) with three replications.

The biodegradable film (0.008 mm thickness, 1.4 m width) was manufactured by BASF in Germany from starch and other biological materials derived from corn straw and renewable resources. Straw mulching used local oat straw at a rate of 9 $\mathrm{t \cdot hm^{-2}}$, cut into 5-10 cm segments and evenly distributed in furrows, then covered with 4-5 $\mathrm{t \cdot hm^{-2}}$ of fine soil to prevent wind displacement. Liquid film, produced by Beijing Jinshanghe Biotechnology Co., was mixed with water at a 1:15 ratio before application. After stirring for 5-10 minutes to ensure complete dissolution, the solution was sprayed uniformly onto furrow surfaces at a rate of 90 $\mathrm{kg \cdot hm^{-2}}$ of powder (1,440 $\mathrm{kg \cdot hm^{-2}}$ of solution), with a service life of 60-90 days.

The experimental site had been planted with potatoes for six consecutive years before 2013. After potato harvest in 2012, the field was plowed and harrowed once. Seven days before sowing (April 13, 2013), the field was prepared, plots were laid out, and ridges were formed and mulched. Based on local fertilization practices, 420 $\mathrm{kg \cdot hm^{-2}}$ of calcium superphosphate and 220 $\mathrm{kg \cdot hm^{-2}}$ of urea were applied as basal fertilizer on April 19, 2013, mixed and incorporated into the soil at a depth of 20-30 cm.

Maize and sorghum were sown on April 20, 2013. Each plot contained three furrows and four ridges, with each furrow covering 6 $\mathrm{m^2}$ (10 m length × 0.6 m width) and total planting area of 18 $\mathrm{m^2}$ per plot. Maize planting density was 5.25$×10^{4}$ plants $\cdot$ $\mathrm{hm^{-2}}$ at 3-5 cm depth, with 50 cm row spacing and 32 cm plant spacing, arranged in two rows per furrow (six rows per plot). Sorghum density was 1.05$×10^{5}$ plants $\cdot$ $\mathrm{hm^{-2}}$ with 15 cm plant spacing, otherwise similar to maize. Immediately after sowing, furrows were mulched with biodegradable film, straw, or liquid film to protect soil moisture. Liquid film was applied twice during the growing season on April 22 and June 28. No topdressing or irrigation was applied during the growth period. Weeding was done manually on May 10, June 15, and July 23, with strict prohibition of ridge damage. Harvest dates were October 15 for maize and October 1 for sorghum. After harvest, straw and film residues were incorporated into the soil at 20-30 cm depth.

1.4 Sample Collection and Measurement

Soil temperature at various depths (5, 10, 15, 20, and 25 cm) in furrows and ridges was measured using mercury-in-glass geothermometers throughout the growing season. Measurements were taken at furrow centers and ridge tops every 5 days at 8:00, 14:00, and 18:00, with daily averages calculated from the three readings.

Soil water content in furrows was measured at the center position: one day before sowing (April 19, 2013), one day after harvest (October 16 for maize, October 2 for sorghum), and after rainfall events (>5 mm). Soil water content was determined by the oven-drying method (105 °C for 10 h) to a depth of 140 cm, with 10 cm increments in the 0-20 cm layer and 20 cm increments below 20 cm.

Soil water storage and water use efficiency (WUE) were calculated using the following formulas [25]:

$$W = \sum_{i=1}^{n} \theta_i \times BD_i \times H_i \times 10$$

$$ET = P + Re \times P \times \frac{h_1}{h_2} + (W_1 - W_2)$$

$$WUE = \frac{GY}{ET}$$

Where:
W is soil water storage (mm);   is soil mass water content (%); BD is soil bulk density ($g \cdot cm^{-3}$), measured as 1.27, 1.32, 1.40, 1.45, 1.29, 1.26, 1.24, and 1.18 $g \cdot cm^{-3}$ for depths of 0-10, 10-20, 20-40, 40-60, 60-80, 80-100, 100-120, and 120-140 cm, respectively; H is soil layer thickness (cm); 10 is a conversion coefficient; ET is crop evapotranspiration (mm); P is total rainfall during the crop growth period (mm), measured by an automatic weather station 50-100 m from the experimental site (rainfall interception by mulches was ignored); Re is average runoff efficiency of biodegradable film ridges (74% annually, based on Wang et al. [25]); h_1 and h_2 are ridge and furrow widths (cm), respectively; W_1 and W_2 are soil water storage in the 0-140 cm layer one day before sowing and one day after harvest, respectively; WUE is water use efficiency ($kg \cdot hm^{-2} \cdot mm^{-1}$); and GY is net grain yield from ridge-furrow planting ($kg \cdot hm^{-2}$).

The milk-to-dough stage represents the optimal silage period for maize and sorghum [26]. During this period (September 5 for maize, August 30 for sorghum), 18 plants per plot (6 per furrow) were sampled to determine fresh silage yield. At maturity (October 15 for maize, October 1 for sorghum), 18 plants per plot were harvested, oven-dried at 105 °C for 1 hour, then at 75 °C to constant weight to determine aboveground biomass (grain + straw). Remaining plants were used to measure grain yield. Net grain yield (GY) was calculated as plot grain yield divided by planting area (furrow area), while reported grain yield was plot grain yield divided by total plot area (ridge + furrow).

Data analysis was performed using Microsoft Excel for graphing and SPSS 17.0 for significance testing and one-way ANOVA.

2.2 Effects of Furrow-Mulching Materials on Soil Temperature

Topsoil (0–25 cm) temperature in furrows and ridges varied throughout the crop growth period [Figure 3: see original paper]. Temperature differences among furrow treatments were more pronounced than among ridge treatments. During early growth when crop canopies were small, furrow and ridge surfaces received direct solar radiation, making ridge-furrow effects on soil temperature particularly significant at the seedling stage. These differences diminished as the growing season progressed and canopies expanded, especially after early September when temperatures declined and mulching materials degraded. Following continuous or heavy rainfall (e.g., 52.4 mm from July 7-12), temperature differences among treatments became negligible. Twenty-four hours after this rainfall event, furrow soil temperatures for maize were 19.1 °C, 19.2 °C, 18.8 °C, and 19.3 °C under no mulching, liquid film, straw, and biodegradable film, respectively, while ridge temperatures were 19.9 °C, 20.7 °C, 20.0 °C, and 19.5 °C. For sorghum, corresponding furrow temperatures were 19.0 °C, 19.0 °C, 18.8 °C, and 19.2 °C, with ridge temperatures of 19.4 °C, 20.0 °C, 19.1 °C, and 19.7 °C.

Averaged across the entire growth period, liquid film and biodegradable film mulching increased maize furrow topsoil temperature by 0.2 °C and 1.0 °C, respectively, while straw mulching decreased it by 1.1 °C compared with no mulching. For sorghum, liquid film and biodegradable film increased temperature by 0.2 °C and 1.1 °C, respectively, while straw decreased it by 1.3 °C. Mulching effects on sorghum were similar to those on maize: biodegradable film provided clear warming, straw caused cooling, and liquid film had minor warming effects. Although maize canopies were taller than sorghum canopies with greater shading effects, canopy impacts on topsoil temperature were similar between crops.

2.3 Effects of Furrow-Mulching Materials on Soil Water Storage

Soil water storage in furrows fluctuated with rainfall, temperature, evaporation, and crop transpiration [Figure 4: see original paper]. During early growth (0-30 days after sowing), low temperatures, limited rainfall, and slow crop growth resulted in non-significant differences among treatments. Winter 2012 (October–December) and spring 2013 (January–March) precipitation totaled only 19.4 mm and 6.1 mm, respectively, leaving soil water storage at its lowest at sowing. Higher autumn rainfall resulted in maximum water storage at the dough and maturity stages. Throughout most of the growing season, straw and biodegradable film mulching maintained significantly higher soil water storage than no mulching or liquid film, with no significant differences between straw and biodegradable film or between no mulching and liquid film.

Averaged across the entire growth period, liquid film, straw, and biodegradable film mulching increased 0–140 cm soil water storage by 0.4 mm, 21.5 mm, and 8.6 mm, respectively, for maize, and by 2.3 mm, 21.0 mm, and 10.9 mm for sorghum, compared with no mulching. Mulching reduced ineffective evaporation from bare soil, particularly straw mulching, which lowered surface temperature, slowed crop growth, reduced transpiration, and maintained higher water storage. Liquid film had minimal effects on water storage, while biodegradable film reduced evaporation but supported faster crop growth and higher transpiration, resulting in lower water storage than straw mulching.

2.4 Effects of Furrow-Mulching Materials on Silage Yield and Grain Yield

Biodegradable film mulching significantly increased maize silage yield compared with no mulching and liquid film, which in turn significantly outperformed straw mulching . For sorghum, biodegradable film produced significantly higher silage yield than all other treatments, with no significant differences among the latter. Biodegradable film also significantly increased grain yield and aboveground biomass for both crops compared with all other treatments, which did not differ significantly among themselves.

Compared with no mulching, liquid film and biodegradable film increased maize silage yield by 0.4% and 10.4%, grain yield by 1.6% and 11.3%, and aboveground biomass by 0.7% and 7.3%, respectively. For sorghum, corresponding increases were 0.2% and 10.9% for silage, 1.1% and 11.8% for grain, and 1.6% and 9.4% for biomass. Straw mulching reduced all yield components: maize silage, grain, and biomass decreased by 2.9%, 2.2%, and 1.9%, respectively, while sorghum decreased by 0.7%, 1.4%, and 1.0%. Biodegradable film improved soil moisture and temperature, shortened growth duration, and promoted early development and yield formation. Although straw mulching increased water storage, its cooling effect delayed seed germination, seedling growth, and phenological development, ultimately reducing yields. Liquid film provided inferior water and temperature conservation and degraded faster than biodegradable film, resulting in limited yield benefits.

2.5 Effects of Furrow-Mulching Materials on Evapotranspiration and Water Use Efficiency

Evapotranspiration (ET), comprising soil evaporation and plant transpiration, is a critical component of hydrological cycles in terrestrial ecosystems and a key source of water and energy for crop growth. Across the entire growth period, ET was significantly higher under no mulching and liquid film than under biodegradable film and straw, with no significant differences within each pair. The ranking was: no mulching liquid film > biodegradable film straw.

Water use efficiency (WUE), defined as the ratio of net grain yield to field water consumption [25], is a vital indicator of crop water utilization efficiency. Improving precipitation use efficiency is central to sustainable agriculture in the Loess Plateau region. Mulching materials alter soil evaporation and surface temperature, thereby affecting soil moisture, crop growth, and water consumption. Biodegradable film mulching significantly increased WUE compared with all other treatments, which did not differ significantly. Specifically, liquid film, straw, and biodegradable film increased maize WUE by 0.9, 0.5, and 4.9 $\mathrm{kg} \cdot \mathrm{hm}^{-2} \cdot \mathrm{mm}^{-1}$, respectively, and sorghum WUE by 0.3, 0.4, and 2.7 $\mathrm{kg} \cdot \mathrm{hm}^{-2} \cdot \mathrm{mm}^{-1}$, respectively. Average WUE for maize was 1.9 times that of sorghum across all treatments.

Discussion

Mulching materials in ridge-furrow systems create surface barriers that reduce water and heat exchange between soil and atmosphere, thereby conserving moisture for crop production. Conventional tillage suffers from direct raindrop impact that destroys soil aggregates, reduces porosity, and decreases infiltration. Surface mulching protects soil structure, maintains porosity, and enhances infiltration. Ridge-furrow systems collect runoff from ridges, combine it with direct precipitation in furrows, convert ineffective rainfall into effective rainfall, and reduce ineffective evaporation, thereby increasing soil moisture in the crop root zone.

As the growing season progresses, liquid film and biodegradable film gradually degrade, diminishing their water conservation effects. Our results show that biodegradable film provided the greatest WUE improvements, increasing maize and sorghum WUE by 4.9 and 2.7 $\mathrm{kg} \cdot \mathrm{hm}^{-2} \cdot \mathrm{mm}^{-1}$, respectively. These findings align with previous research: Zhu et al. reported that ridge-furrow planting increased spring wheat grain yield by 17.6–72.8% and WUE by 3.05 $\mathrm{kg} \cdot \mathrm{hm}^{-2} \cdot \mathrm{mm}^{-1}$ compared with flat planting, while Ren et al. found that ridge-furrow planting increased spring maize yield by 83%, 43%, and 11% and WUE by 77%, 43%, and 10% under rainfall conditions of 230 mm, 340 mm, and 440 mm, respectively, with yield gains decreasing as rainfall increased.

Field observations indicated that the rainy season began in mid-June. During early growth, liquid film and biodegradable film provided water conservation and warming effects similar to conventional plastic film, but offered advantages of being labor-saving, non-polluting, and requiring no post-harvest removal, though their economic costs and durability require further investigation.

Conclusion

Biodegradable film mulching significantly increased topsoil temperature (by 1.0 °C for maize and 1.1 °C for sorghum) and improved soil water storage (by 8.6 mm for maize and 10.9 mm for sorghum) compared with no mulching. It substantially increased crop yields: maize silage, grain, and biomass increased by 10.4%, 11.3%, and 7.3%, respectively; sorghum increased by 10.9%, 11.8%, and 9.4%. WUE improvements were also greatest under biodegradable film (4.9 $\mathrm{kg} \cdot \mathrm{hm}^{-2} \cdot \mathrm{mm}^{-1}$ for maize, 2.7 $\mathrm{kg} \cdot \mathrm{hm}^{-2} \cdot \mathrm{mm}^{-1}$ for sorghum). In contrast, straw mulching cooled the soil and reduced yields, while liquid film provided modest benefits. Considering crop performance, water use efficiency, and environmental protection, biodegradable film is the most suitable furrow-mulching material for ridge-furrow rainwater harvesting systems in the semiarid Loess Plateau region.

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