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Fully biodegradable film to boost rainfed maize (*Zea mays* L.) production in semiarid Kenya: An environmentally friendly perspective

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ABSTRACT

Conventional polyethylene plastic film mulching has been widely used, but its subsequent plastic residue pollution received widespread concern. Fully biodegradable film mulching is viewed as a potential substitution solution, however, it is generally thought not to be efficient as conventional plastic film mulching in field productivity and economic harvest. A two-year field experiment using a newly produced fully biodegradable film was conducted in semiarid Kenya in 2016 and 2017 respectively. Five treatments were designed as: 1) ridge-furrow mulching (RFM) with transparent plastic film (RFMT), 2) RFM with fully biodegradable film (RFMD), 3) RFM with black plastic film (RFMB), 4) RFM with grass straw (RFMG) and 5) traditional flat planting without mulching (FP) as CK. We found that RFMD achieved the similar evaporation-restricted, yield-increased and water-saving effectiveness as RFMT and RFMB did across two growing seasons. The RFMD lowered evaporation by 58.1 mm, while increasing grain yield by 70.16 %, above-ground biomass by 77.7 % and water use efficiency (in reference to grain yield) (WUE_G) by 131.8 % in comparison with CK respectively. Furthermore, RFMD increased net economic income by 49.8 % in 2016 and 42.0 % in 2017 respectively relative to CK, as RFMT and RFMB did. It is noted that the degradable film used in this experiment is a non-polyethylene material and still can be maintained for 60 days in a fine physical state. Also, average soil temperature was significantly elevated by 1.6 °C in 2016 and 1.8 °C in 2017 in RFMD respectively, in comparison with CK, which was beneficial to crop growth and grain filling particularly in relatively cool long rainy season. Considering residual film pollution, the biodegradable film showed reliable advantages in environmental friendliness and field productivity. Therefore, it might be a promising farming solution to boost rainfed maize production and environmental sustainability in east African Plateau.

1. Introduction

In arid and semi-arid rain-fed agricultural areas, plastic film mulching can increase soil temperature (Li et al., 1999), maintain soil moisture and restrain evaporation (Chakraborty et al., 2008), reduce soil erosion (Arnhold et al., 2013) and improve soil structure and fertilizer efficiency (Li et al., 2001). Mulching can reduce disease and insect pests and inhibit weeds (Bhardwaj, 2013). It has been widely used as an important farming technology because of its low investment, convenient operation and significant improvement on water use efficiency, crop productivity and revenue (Zhou et al., 2012; Mo et al., 2016; Wang et al., 2016). However, it is difficult to completely recycle residual polyethylene film for current plastic recycling technology (Yan et al., 2014a), and the degradation period of residual film is more than 200 years (Ohtake et al., 1998a; Otake et al., 1995). Long-term film mulching could cause an irreversible impact on field ecosystem (Ohtake et al., 1998b). The accumulation of residual film in soil is found to negatively influence the absorption of water and nutrition in root system, the changes in soil structure, the emergence of seeds and the yield of crops (Yan et al., 2014b). The so-called white pollution is becoming increasingly serious, which not only threatens natural environment but also could affect the survival of human being.

There has been a great demand to explore non-polluting and environment-friendly biodegradable agricultural film in terms of white

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pollution and ecosystem sustainability (Li et al., 2014). Over last decades, to explore fully biodegradable plastic film has become one of major goals in film mulching agriculture. The new biodegradable film is required to achieve the similar effect as conventional polyethylene film, maintaining high productivity and complete degradation into water and carbon dioxide. These advantages help reduce the white pollution and protect environment (Witt et al., 2001; Moreno and Moreno, 2008; Yao et al., 2017). In ridge-furrow film mulching system, fully biodegradable plastic film can be completely degraded in soil, while increasing corn productivity and water use efficiency (Conway and Toenniessen, 2003). Over last decades, biodegradable film has been tested in Europe and the United States (Shah et al., 2008), however little information is available for this issue in African regions.

Currently, degradable plastic films primarily comprises of three types, including photodegradation, biodegradation/photodegradation and biodegradation (Kasirajan and Ngouajio, 2012). Among three types of film, photodegradable plastic film is first studied and applied. Previous study showed that photodegradation would cease if film surface was covered with soil, in which degradation rate was difficult to control accurately. Since film residues cannot be completely degraded, this type of film failed to be widely used (Kasirajan and Ngouajio, 2012). On the other hand, biodegradable film can be degraded by microorganisms in natural environment. Generally, the degradation of mulched film depends on soil microbial species which can decompose polymer and surface structure (Zhao et al., 2004). Therefore, it is necessary to elucidate the hydrothermal effect, the degradation characteristics and the productive effects on crop yield and economic benefits when applying fully biodegradable plastic film.

In addition, biodegradable film is generally divided into two types, i.e. additive biodegradable plastic film and fully biodegradable film. Additive biodegradable plastic film is produced with conventional plastic materials combined with biodegradable materials or additives, such as starch and cellulose. In general, typical biodegradable plastic film is produced with polyethylene starch biodegradable plastic substance. However, fully biodegradable film consists of the substances that can be completely decomposed and metabolized by microorganisms, and their final metabolites are CO_2 and H_2O without any pollution to ecological environment (Ran et al., 2003). These substances briefly include polylactic acid (PLA), polycaprolactone (PCL), polyhydroxybutyrate (PHB), polybutylene succinate (PBS), polybutylene succinate adipate (PBSA) and polybutylene adipate/terephthalate (PBAT). PBAT has been proven to be completely degraded by microorganisms under certain environmental conditions and does not harm the environment (Witt et al., 2001).

However, to the most extent, the productivity and economic efficiency of fully biodegradable agricultural mulch have been questioned. To provide a scientific basis on the fully biodegradable film application in semiarid Africa, it is necessary to clarify its effects on water conservation, production and degradation in this area. Generally, the degradation of fully biodegradable film is primarily affected by bacteria, fungi, and organisms that exist in soil (Shah et al., 2008). This phenomenon frequently takes place through three ways. First, plant growth, root system and biological process might destroy the mechanical properties of film membrane (Shah et al., 2008). Second, different enzymes produced by soil microorganisms are able to exert certain enzymatic activeness to film material, and result in a performance decline in film properties. Third, the large number of soil bacteria and fungi attached on the surface of mulching film are also likely to affect the mechanical properties of film material (Shah et al., 2008). In a word, the degradation process of fully biodegradable film is closely related to the types of film material and microorganisms in soil environment. Film sheets are more easily degraded under the conditions conducive to microbial growth, such as suitable temperature, pH, moisture, and sufficient carbon source (Shah et al., 2008). Maize is a staple crop in Kenya, but its productivity remains at a low level for long time. In this study, maize was chosen as experimental material. We evaluated the effects of the fully biodegradable film on maize productivity under Africa's unique geographical environment and climate, such as the yield, economic efficiency, and water use efficiency compared with conventional plastic film.

2. Materials and methods

2.1. Experimental materials

The fully biodegradable film used in this study is produced by Guangzhou Kingfa Sci. & Tech. Co., Ltd, China, and it is primarily comprised of polybutylene adipate/terephthalate (PBAT). The fully biodegradable film is 0.012 mm thick, and the degradation induction period is around 60 days. The conventional plastic film is produced by Lanzhou Goldland Plastic Co., Ltd, China. Conventional black film is 0.014 mm thick, and conventional transparent film is 0.012 mm thick. The grass straw for mulching was free and obtained near the experimental field before sowing. It contained total nitrogen by 7.0 mg g^{-1} and total phosphorus by 1.1 mg g^{-1} respectively. Before sowing, grass straw was cut into the strips in 5 − 10 cm length and then applied on soil surface manually at the rate of 6 t ha^{-1} in both growing seasons.

2.2. Experimental site description

The experimental site is located at the experimental farm at the Jomo Kenyatta University of Agriculture and Technology (JKUAT), which belongs to Juja, Kiambu County, Kenya. It is 35 km from Nairobi with an altitude of 1520 m (1°06´S, 37°01´E) and a warm and temperate climate (Muthuri et al., 2005). The multi-year average temperature is 19.7 °C, and the average annual rainfall is 856 mm with the bimodal characteristics, i.e., primary and secondary peaks in April and November, respectively (Muthuri et al., 2005). The least amount of rainfall occurs in July with an average of only 12 mm, and the highest precipitation occurs in April with an average of 175 mm. March is the hottest with 21.3 °C, and July is the coldest with 18.4 °C. The mean annual maximum and minimum temperatures are 22.7 °C and 10.4 °C, respectively. The mean annual potential evaporation is 5.05 mm d^{-1}. The experimental site is the part of the mapping unit LPD by Wanjogu and Kamoni (1986), with a flat topography. The local soil is poorly drained, dark grey and extremely firm cracking clay.

The pH ranges from 5.2–5.8 in the topsoil and from 4.8–7.0 in the subsoil. The soil type belongs to Chromic Vertisols with low fertility in shallow soil. The local sandy soil clay can support drought resistance crops, such as soya beans, sunflowers and ranching. The soil bulk density is 1.49 g cm^{-3}, and the field water-holding capacity is 34.65 % (determined gravimetrically).

2.3. Experimental design and field management

The ridge-furrow mulching (RFM) farming system includes alternating ridges and furrows and mulching (RFMs). A core configuration of RFM system is alternating ridges and furrows, and each ridge-furrow unit comprises a wide-low ridge (0.6 m in width and 0.10 m in height) and a narrow-high ridge (0.4 m in width and 0.15 m in height), the naturally occurring furrows at the junction between the wide-low ridge and the narrow-high ridge can be used to collect water and grow crops. Two differently sized ridges serve as the areas of producing rainwater run-off, and the wide-low ridge can also be used for walking and field operation. It should be noted that the gauges of ridges are not fixed but can be modified according to local rainfall and thermal conditions. Crops are usually planted in furrows in order to use water more effectively. The mulching materials vary from crop types, farm resources, planting environment, climate conditions and soil characteristics. Before sowing, films (including transparent plastic, black plastic and full-biodegradable film) are laid over the plot where two pieces of plastic films are jointed in the midline between the wide and narrow ridges, and the joint is fixed stably by placing soil on the top of film. Weeds can be cleared manually by lifting the film at the junction of two pieces of film sheets during the growing season.

The experiment was arranged in a randomized, complete block design with three replicates in both growing seasons. Each plot was 5 m long and 4.8 m wide, and the bare ridges were constructed around each plot to prevent runoff. Each plot was surrounded by a 1.0 m wide path, and 75 kg rotten sheep manure was applied to each plot. The experiment comprised four mulching treatments as follows: 1) ridge-furrow with mulching transparent plastic film (RFMT), 2) ridge-furrow with mulching full-biodegradable film (RFMD), 3) ridge-furrow with mulching black plastic film (RFMT), 4) ridge-furrow with mulching grass straw (RFMG), and 5) conventional flat planting without mulching (FP) as the control (CK). The planting density was 145 plants per plot (equal to 6.0×10^4 plants per hectare) with 35 cm between the plants. For both growing seasons, China's middle-late mature grain and forage hybrid maize variety Yuyuan7879 was sown in the furrows using a hole-sowing machine. After harvest, all the plastic film residues were cleared by hand. The lands remained clean to avoid any other influence on soil and water conservation in the experimental site across two growing seasons.

2.4. Soil and plant samplings

2.4.1. Soil water storage

Soil water content (SWC, %) was determined gravimetrically each 20 days at every 20-cm increment within a depth of 120 cm across each growing season. In each plot, soil samples were taken in the centre of furrows with three replicates using a soil auger (5 cm diameter, 20 cm height). The SWC was also measured before sowing and after harvesting. Soil bulk density was determined throughout the soil profile (0–120 cm depth), and its average value was 1.49 g cm^{-3}. Soil water storage (SWS, mm) was calculated as follows:

$$SWS = SWC \times \triangle b \times H$$

Where SWC is the soil water content (%), $\triangle b$ is the soil bulk density (g cm^{-3}), and H refers to as the thickness of the soil layer (mm).

2.4.2. Water use efficiency

Water use efficiency (WUE) was calculated as the ratio of grain yield or aboveground biomass per unit area to total water consumption (evapotranspiration, ET) over whole growing season. In the study site, crop growth was completely dependent on precipitation, and local precipitation was too low to entail drainage below 1 m underground. There was no runoff due to the ridges around each ridge-furrow plot, and no irrigation was applied throughout whole growing season. Seasonal evapotranspiration (ET) in each plot was determined using the equation:

$$ET = P + \triangle W$$

Where P is total precipitation in one growing season (mm), and $\triangle W$ is the difference in SWS before sowing and after harvesting. The water use efficiency of grain yield (WUE_G) and of aboveground biomass (WUE_A) was calculated as follows:

$$WUE_G = Y/ET;\ WUE_A = A/ET$$

Where Y is grain yield (kg ha^{-1}, A is aboveground biomass (kg ha^{-1}, and ET is the evapotranspiration amount in each growing season.

2.4.3. Biomass and yield production

Growth traits were recorded each 20 days after sowing (DAS) until the maturity stage. Three individual plants were randomly chosen in each plot and marked to be measured for plant height and leaf area. Leaf area was calculated as follows (Mckee, 1964):

$$\text{Leaf area } (cm^2 \text{ per plant}) = \text{leaf length (cm)} \times \text{leaf width (cm)} \times 0.75,$$

At the harvesting stage, three rows of plants in the middle of each plot were sampled to determine grain yield and yield components. Grain yield, aboveground biomass weight, corncob length, corncob diameter, corncob weight, bare tip length, bract weight and kernel number were recorded for each plot. All the biomass samples were placed in a forced-air oven at 105 °C for 1 h and at 80 °C for a minimum of 72 h.

2.4.4. Profitability analysis

In this study, the input included the values of labour and materials investment. The labour work included land preparation, field management, sowing and harvesting. In the RFM treatments, additional labour work also comprised ridge-furrow making and film/grass straw mulching. Since grass resource was freely available around the fields, we only considered the labour cost in collecting grass straw materials. The output was evaluated based on the economic harvest of grain and hay yields. The net income in each treatment was determined by calculating the differences in the values between total output and total input. In addition, the output/input ratio in each treatment was estimated using the output values divided by the input values.

2.5. Fully biodegradable film degradation velocity

The fully biodegradable film for the experiment was cut into the pieces with the size of 35 cm long and 33 cm wide. The ridge was mulched after weighing, and the process was conducted with three replicates. The film sheets were weighed and recorded once every 20 days. Degradation velocity was decided by the following formula:

Degradation velocity = (initiation weight-current weight)/initiation weight × 100 %

2.6. Statistical methods

A one-way ANOVA using SPSS 18.0 software was performed to test the differences among the treatments. Multiple comparisons were made using Duncan's test at the 5% level, i.e. indicating significance at $P < 0.05$. The figures were drawn in Origin 8.0 (Microcal Software Inc. Northampton, Massachusetts, USA).

3. Results and discussion

3.1. Effects of the RFMs on grain yield, biomass and water use efficiency across two growing seasons

RFMT, RFMD, RFMB increased soil temperature, especially in the RFMT treatment (Fig. 3). This increase was mainly due to transparent film being able to reflect more solar radiation and minimize the extent of the changes in soil temperature while increasing the irradiance around plant canopy (Liu et al., 2009). Increased temperature promoted the growth of maize. The results were consistent with those of Liu (Liu et al., 2009) and Zhao (Zhao et al., 2014), who reported that the yields of maize and potato, two staple crops in the Loess Plateau, China were significantly increased under the RFMT and RFMB. The similar results were also observed by Han (Han et al., 2013) and Xiaoli (Xiaoli et al., 2012), in which the yield and WUE of maize were increased significantly under the RFMs.

Moreover, leaf area in the RFMs was much greater than that of CK (data not shown), which was a key driving force for biomass accumulation and yield production. The RFMs also improved the components of yield formation, such as grain number and ear length (data not shown here, but indicated in the supplementary material tables). In addition to leaf area, ear length was another important indicator, since ear photosynthesis significantly contributed to final grain yield,

Table 1
Comparisons of grain yield, above-ground biomass and water use efficiency among various treatments at experimental site of Kenya over two growing seasons.

Treatment	Year	Rainfall (mm)	ET (mm)	ΔSWS	Grain yield (kg ha^{-1})	Above-ground biomass (kg ha^{-1})	WUE_G (kgha^{-1} mm^{-1})	WUE_A (kg ha^{-1} mm^{-1})
RFMD	2016	133.4	169.6 a	36.2 a	4762.8 a	13892.7 a	28.08 a	81.91 a
RFMT			165.5 a	32.1 a	4953.9 a	14856.3 a	29.93 a	89.77 a
RFMB			164.3 a	30.9 a	4612.5 a	13476.6 a	28.07 a	82.02 a
RFMG			195.7 b	62.3 b	3076.9 b	8967.9 b	15.72 b	42.25 b
FP (CK)			225.4 c	92 c	2799.1 b	7843.8 b	12.42 b	34.8 b
RFMD	2017	111.2	152.4 a	41.2 a	3969.1 a	11473.5 a	26.04 a	75.29 a
RFMT			146.7 a	35.5 a	4128.3 a	12837.8 a	28.14 a	87.51 a
RFMB			147.3 a	36.1 a	3753.8 a	11287.7 a	25.48 a	76.63 a
RFMG			177.4 b	66.2 b	2564.1 b	7382.9 b	14.45 b	41.62 b
FP (CK)			212.8 c	101.6 c	2332.5 b	6437.4 b	10.96 b	30.25 b

Abbreviations: Rainfall, total rainfall from planting to harvesting; △SWS, difference in soil water storage in the 0–120 cm layer within growing season; ET, evapotranspiration. Values are given as means of three replications. Values followed by different letters within a column are significantly different ($P < 0.05$).

especially under harsh environments (Pelleschi et al., 1997). In this study, increased ear length in the RFMs acted as a significant photosynthetic contributor to grain filling. In the semiarid regions without water resources for irrigation, agricultural production is highly dependent on rainfall, especially in the east African Plateau (EAP) region. Our observations indicated that the RFM system would be an effective farming practice to improve rainwater harvesting efficiency and crop productivity in the EAP. It can be predicted that the RFMs would increase water availability for crops and improve and stabilize agricultural production in other similar areas as the EAP.

The yield and biomass in the FP (CK) in 2016 were 2799.1 kg ha^{-1} and 7843.8 kg ha^{-1}, respectively (Table 1). In 2016, the yield in the RFMG was increased by 9.92 %, comparing with CK. Furthermore, the yield in RFMB, RFMD and RFMT was increased by 64.79 %, 70.15 % and 76.98 % respectively, in comparison with that of CK. There was no significant difference in grain yield among three mulching film treatments. Similarly, the biomass in the RFMG was elevated by 14.33 %, and that of the RFMB, RFMD, and RFMT was increased by 71.81 %, 77.12 % and 89.4 % respectively, comparing with CK. There were no significant differences among three mulching film treatments. The WUE_G and WUE_A of CK were 12.42 kg· ha^{-1} mm^{-1} and 34.8 kg ha^{-1} mm^{-1} in 2016, respectively. The WUE_G of the RFMG was increased by 26.57 %, compared with CK. The yield of RFMB, RFMD and RFMT was increased by 126.01 %, 126.09 %, and 140.98 %, respectively. There were no significant differences among three mulching film treatments. In 2016, the WUE_A of RFMG was increased by 21.41 % compared with CK, and the yield of RFMB, RFMD and RFMT was increased by 135.69 %, 135.37 % and 157.96 %, respectively. There were no significant differences among three mulching film treatments (Table 1).

In 2017, the trends in grain yield, aboveground biomass, WUE_G, and WUE_A were generally similar as in 2016. In light of rainfall amount, 2017 growing season was drier than 2016 growing season, and therefore grain yield and aboveground biomass were lower in 2017 than those of 2016. In 2017, the FP (CK) treatment harvested grain yield and aboveground biomass of 2332.2 kg ha^{-1} and 6437.4 kg ha^{-1} respectively, while the RFMD achieved 3969.1 kg ha^{-1} and 11473.5 kg ha^{-1} for both parameters respectively. As expected, the RFMD achieved significantly greater WUE_G and $WUE_{A,}$ up to 26.04 kg ha^{-1} mm^{-1} and 75.29 kg ha^{-1} mm^{-1} respectively. The WUE_G and WUE_A were generally improved up to 8.06 % and - 2.15 % in RFMT, and 16.23 % and 1.48 % in RFMB respectively, in comparison of that of RFMD. However, there were no significant differences in both parameters among three film mulching treatments (Table 1).

In this study, another critical parameter was the degradation rate of film sheets. According to the observation, the fully biodegradable film began to crack on the 60th day after sowing, and the degradation rate in 2016 and 2017 was 7.4 % and 5.8 % on the 70 th day respectively (Fig. 2). At the early stage, degradation rate was generally low when the biodegradation process was not activated. It turned to be increased drastically since the 80th day after sowing. The degradation rate on the 140th day after sowing was up to 55.6 % and 51.1 % in 2016 and 2017 respectively, and on the 160th day after sowing was massively enhanced to 70 % and 68.4 % in 2016 and 2017, respectively (Fig. 2). Comparatively, the degradation rate in 2017 was slightly lower than that of 2016, which may be because soil moisture was relatively lower in 2017 than that of 2016. Relatively drier soil generally resulted in poorer biological activity, and led to lower degradation speed.

3.2. Effects of the RFMs on field evapotranspiration over two growing seasons

The monthly average temperature from May to September during previous 8 years was 19.3 °C, 18.7 °C, 18.4 °C, 19.2 °C and 20.4 °C, respectively (Fig. 1). To some extent, two testing years appeared to be warmer. The monthly average temperature from May to September was 1.1 °C, 1 °C, 1.2 °C, 1.1 °C and 1 °C higher in 2016 and 0.9 °C, 1.2 °C, 1.6 °C, 1.1 °C and -0.1 °C higher in 2017 than that of corresponding months over last 8 years, respectively. The mean daily temperature was 0.2 °C lower in May 2017 than that of May 2016, but it was 0.2 °C and 0.4 °C higher in June and July 2017 than that of corresponding months in 2016. In this case, relatively high temperature and drought conditions at mid-term stage generally resulted in higher transpiration rate and insufficient soil moisture in 2017, and the output was therefore lower in 2017 than that of 2016.

We also estimated and compared the evapotranspiration (ET, mm) among the treatments over two growing seasons. In general, the RFM treatments tended to suppress evaporation more effectively, resulting in a lower ET across two growing seasons than CK. In particular, there was a significant difference in ET between film mulching treatments and the others. Therefore, the film mulching treatments exerted better effects on suppressing evaporation than the treatments did. In brief, 2017 growing season was drier than that 2016 growing season according to the in-season aridity (ET/rainfall) indication in this study. That may account for why better growth performance of maize was observed in 2016 than 2017.

In the growing seasons of 2016 and 2017, average annual rainfall was 133.4 mm and 111.2 mm, respectively, and the evapotranspiration in CK was 225.4 mm and 212.8 mm, respectively (Table 1). As expected, the evapotranspiration in RFMG, RFMB, RFMD and RFMT was decreased significantly by 13.18 %, 27.11 %, 24.76 % and 26.57 % in 2016, and 16.64 %, 30.78 %, 28.38 % and 31.06 % in 2017, respectively (Table 1). There were no significant differences among three mulching film treatments during two seasons (Table 1).

In CK, soil water storage (SWS) after harvesting was decreased by 92 mm in 2016 and 101.6 mm in 2017 respectively, comparing with

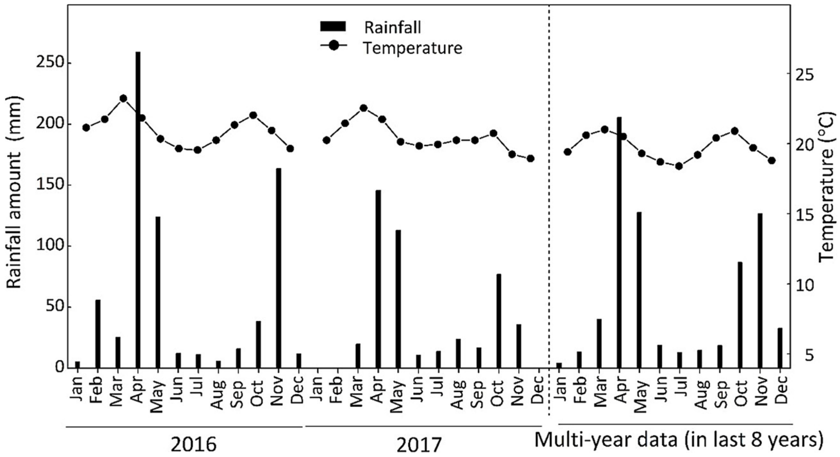
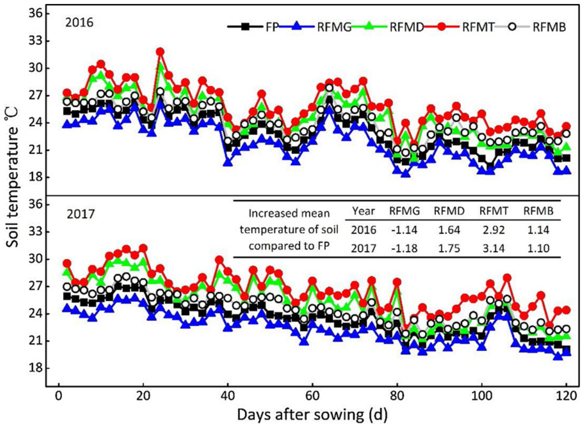


Fig. 1. Dynamics of mean rainfall and air temperature across two-year growing seasons and last 8 years (2009–2016) at experimental site in Kenya.

pre-sowing SWS. The SWS in RFMG, RFMB, RFMD, and RFMT was decreased significantly by 32.28 %, 66.41 %, 60.65 % and 65.11 % in 2016, and 34.84 %, 64.47 %, 59.45 % and 65.06 % in 2017 respectively, comparing with that of CK. There were no significant differences among three mulching film treatments across two growing seasons. Since the 60th day after emergence, biodegradable film started to chap and melt, resulting in a decline in soil water conservation. Therefore, its capacity of evaporation restriction was relatively weaker than that of RFMT and RFMB, which accordingly led to more water loss from soil in RFMD.



Increased mean temperature of soil compared to FP	Year	RFMG	RFMD	RFMT	RFMB
	2016	-1.14	1.64	2.92	1.14
	2017	-1.18	1.75	3.14	1.10

Fig. 3. Dynamics of daily soil temperature in 10 cm depth among various treatments in experimental site of Kenya over two growing seasons.

Although cracks began to appear on the 60th day, cracks appeared in 25 % of fully biodegradable plastic film on the 120th day due to maize canopy closure, and the leaf area and leaf area index enlargement, which resulted in a reduction in soil evaporation and shine radiation on the ground (Jia et al., 2006). In practice, it also slowed down the degradation of fully biodegradable film. Comparatively, RFMG and CK obtained lower plant height, leaf area and leaf area index than RFMD did, and therefore the former had higher evaporation rate and more water loss than the latter. To some extent, the RFMG can block direct sunlight on the soil and soil moisture evaporation, which resulted in a reduction in solar radiation (Mo et al., 2016). In addition, soil temperature in RFMG was lower than that of the others, resulting in relatively poorer growth and grain filling. Taken together, the fully biodegradable film exerted similar effect on increasing water storage as conventional plastic film did across each growing season. Thus, it was

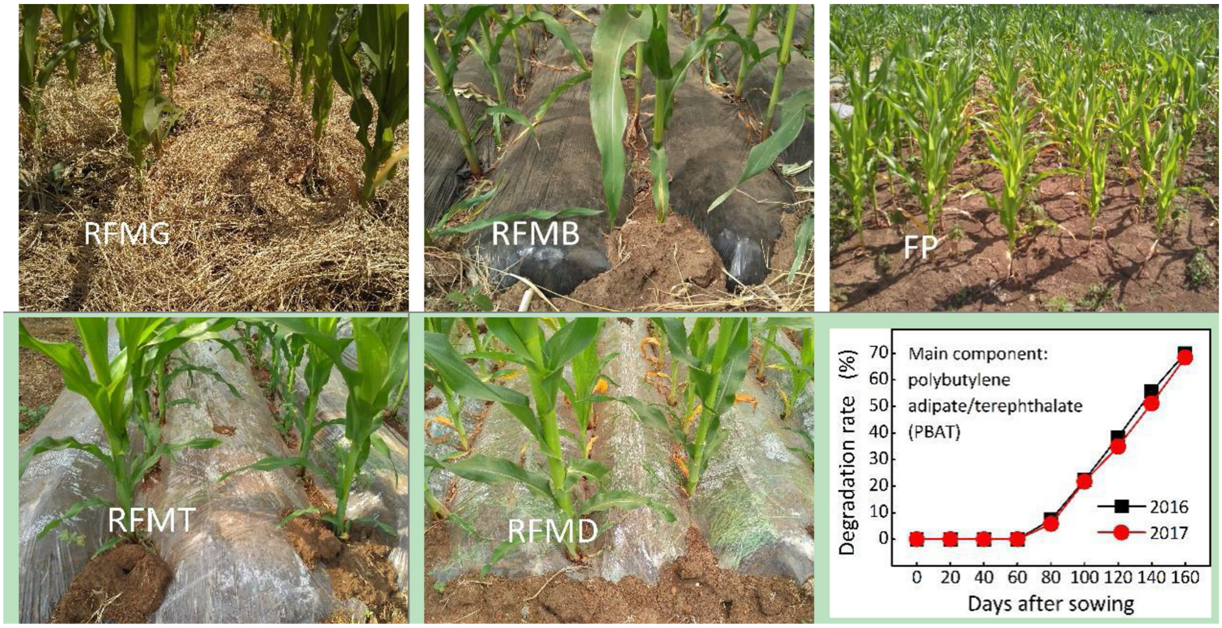


Fig. 2. All treatments at experimental site in Kenya and fully-biodegradable film degradation rate across two-year growing seasons.

supposed to have a potential to replace the conventional plastic film.

In 2016 and 2017, general trend of soil temperature at 10-cm depth was basically similar (Fig. 3). Within 90 days after sowing, daily average soil temperature in various treatments showed that the order from high to low was RFMT, RFMD, RFMB, FP (CK) and RFMG. From 90–120 days after emergence, more cracks appeared in the film sheets of RFMD, which to some extent reduced the warming effect of soil. According to our observation, soil temperature at 10-cm depth in RFMD was slightly lower than that of RFMB. Particularly, soil temperature of RFMG was lower than that of CK. This was mainly because grass straw mulching can avoid direct sunshine radiation on soil surface, while it had fine air permeability and can not stop the heat exchange between soil and air. In such case, the heat preservation and water conservation of grass straw mulching was not as effective as film mulching treatments. Under the condition of film mulching, topsoil can be directly exposed to sunlight irradiation, which can exert a good effect to increase temperature. Also, the heat exchange between air and soil can be effectively isolated by film sheets. Thus, film mulching can achieve the desired effect of the maintenance of temperature and moisture to facilitate plant growth and development. In 2016, soil temperature in RFMG was reduced by 1.10 °C, compared with CK (FP), while it was increased by 1.64 °C in RFMD, 2.92 °C in RFMT and 1.14 °C in RFMB respectively, compared with CK. In 2017, average soil temperature in RFMG was reduced by 1.18 °C, and increased by 1.75 °C in RFMD, 3.14 °C in RFMT and 1.1 °C in RFMB respectively, in comparison with CK. In summary, there was not significant difference in soil temperature and moisture between fully biodegradable and conventional plastic film. And the fully biodegradable film can meet the water-saving and high-yielding demands for dryland maize. Thus, the RFMD farming system can achieve the dual effects of improving maize production and ecological environment protection.

3.3. Analyses on economic benefits over two growing seasons

In present study, the total input for the same treatment in two growing seasons remained same (Table 2). In the control group, the cost of field preparation and management was 175.9 US\$ ha^{-1}, including weeding labor input. The RFMG treatment had additional cost of creating ridge-furrows and mulching grass straw, but the weeding times was reduced. Therefore, its cost of field management was increased by 15.24 %, compared with CK. To most extent, conventional film mulching help resist the growth of weeds, and accordingly reduced the cost of weeding. But it turned to have higher labour costs, such as film sheet installation and film residual removal. Therefore, its total input in field management was increased by 88.63 %, compared with that of CK. In contrast, the relevant cost of RFMD was increased only by 45.99 %, since there was no labour input into removing residual film in this treatment. On the other hand, the labour input cost for sowing and harvesting was 56.5 US\$ ha^{-1} in all the treatments. The seed and fertilizer cost was 117.56US\$ ha^{-1} and 60US\$ ha^{-1} respectively, across all the treatments. In present study, grass straw material was harvested for free in the nearby field, and the expense of mulching material in RFMG was zero. It was noted that the input of fully biodegradable film material was 358.2 US\$ ha^{-1}, i.e. 77.79 % greater than that of transparent film, and 59.98 % greater than that of black film, respectively (Table 2).

In this study, the black film product was added with UV-resistant additives, which was designed for equatorial region of the east African Plateau to prevent excessive ultraviolet radiation. For this reason, the cost of black film was higher than that of transparent film. The economic benefit analysis indicated that total input of CK was 409.96 US\$ ha^{-1}. And total input of RFMG, RFMB, RFMD, and RFMT was elevated by 6.54 %, 92.64 %, 107.11 %, and 87.18 % respectively, in comparison with that of CK (Table 2). According to our observations, the yields of grain and straw in the two growing seasons varied from the treatments, and total output also differed from each other. Total output of CK was 1075.04 US\$ ha^{-1} in 2016 and 892.87 US\$ ha^{-1} in 2017, respectively. Total output of RFMG, RFMB, RFMD and RFMT was improved by 8.94 %, 66.32 %, 71.68 % and 79.70 % in 2016, and 10.96 %, 64.05 %, 71.91 % and 81.84 % in 2017, respectively, comparing with that of CK. Specifically, there was no significant difference in total output between RFMG and CK. Total output of three film mulching treatments was significantly greater than that of CK ($P < 0.05$), while there was no significant difference among three film mulching treatments (Table 2).

Based on the analyses of total input and output, net income of CK was 665.08 US\$ ha^{-1} in 2016 and 482.91 US\$ ha^{-1} in 2017 respectively. Mulching treatments greatly improved the economic benefits across two growing seasons (Table 2). Comparing to CK, RFMG, RFMB, RFMD and RFMT significantly raised net income by 10.42 %, 50.1 %, 49.84 % and 75.09 % in 2016, and 14.71 %, 39.78 %, 42.03 % and 77.31 % in 2017, respectively (Table 2). The data showed that the margin of improvement on net income was basically consistent in 2016 and 2017. The RFMT treatment achieved the greatest net income, up to 1164.5 US\$ ha^{-1} in 2016 and 856.3 US\$ ha^{-1} in 2017 respectively, followed by RFMD and RFMB. And the RFMG harvested the least net income among four mulching treatments (Table 2). Although total output of RFMD was much greater than that of CK, its material cost including purchasing fully biodegradable film was the highest, and its yield and biomass output was lower than that of RFMB and RFMT. In RFMB and RFMT, residual film removal was additional labour input, while in RFMD there was no such input.

In addition, both the ratio of output to input and net income were higher in RFMB and RFMT than those of RFMD. In 2016, the net income of RFMD was 0.17 % and 14.42 % lower than that of RFMB and RFMT,

Table 2
Comparative economic benefits of maize among various treatments at over two growing seasons (unit: US\$ ·ha^{-1}).

Treatments	Year	Labor input		Material input			Total input	Output		Total output	Output/ Input	Net income
		Field managements	Seeding, Harvesting	Plastic sheets	Commercial seeds	Fertilizers, Pesticides		Grain yield	Hay yield			
RFMD	2016	256.8	56.5	358.2	117.6	60	849.1	1428.8 a	416.8 a	1845.6 a	2.17 c	996.6 b
RFMT		331.8	56.5	201.5	117.6	60	767.3	1486.2 a	445.7 a	1931.8 a	2.52 b	1164.5 a
RFMB		331.8	56.5	223.9	117.6	60	789.8	1383.8 a	404.3 a	1788.1 a	2.26 c	998.3 b
RFMG		202.7	56.5		117.6	60	436.8	923.1 b	248.1 b	1171.1 b	2.68 a	734.4 c
FP		175.9	56.5		117.6	60	409.9	839.7 b	235.3 b	1075.1 b	2.62 a	665.1 d
RFMD	2017	256.8	56.5	358.2	117.6	60	849.1	1190.7 a	344.2 a	1534.9 a	1.81 c	685.9 b
RFMT		331.8	56.5	201.5	117.6	60	767.3	1238.5 a	385.1 a	1623.6 a	2.12 b	856.3 a
RFMB		331.8	56.5	223.9	117.6	60	789.8	1126.1 a	338.6 a	1464.8 a	1.85 c	675.1 b
RFMG		202.7	56.5		117.6	60	436.8	769.2 b	221.5 b	990.7 b	2.27 a	553.9 c
FP		175.9	56.5		117.6	60	409.9	699.8 b	193.1 b	892.9 b	2.18 b	482.9 d

Notes: Price per unit for grain was 0.3 US\$ kg^{-1} and price per unit for dry straw was 0.03 US\$ kg^{-1} respectively. Values are given as means of three replications. Values followed by different letters within a column are significantly different ($P < 0.05$).

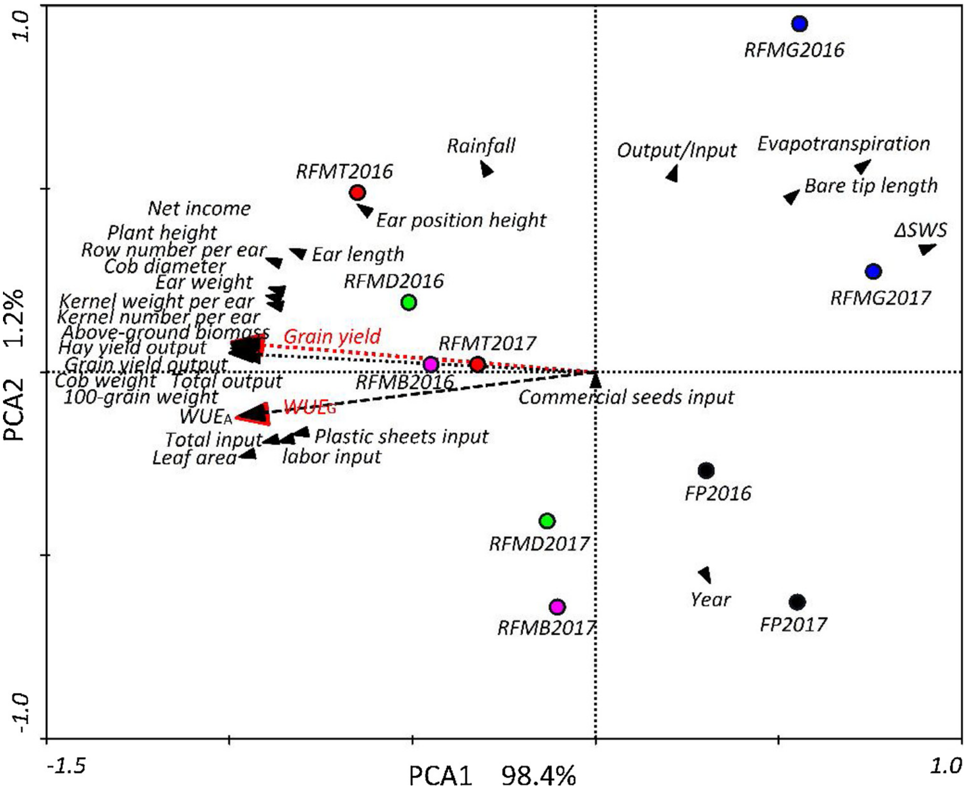


Fig. 4. PCA analysis on morphological characteristics, economic input and output, yield components parameters in all treatments over two growing seasons.

respectively. In 2017, it was higher by 1.61 % and lower by 19.9 % than that of RFMB and RFMT, respectively. In total, the ratio of output to input in RFMD was 3.99 % and 13.66 % lower than that of RFMB and RFMT in 2016, and was 2.53 % and 14.56 % lower than that of RFMB and RFMT in 2017, respectively. Importantly, there was significant difference in the output-to-input ratio between RFMD and RFMT in two years, and no significant difference between RFMD and RFMB (Table 2). The RFMD treatment saved the labour cost for removing residual film. If total cost of fully biodegradable film group was the same as that of transparent film group, the net income of two groups would be almost the same. However, if total cost of fully biodegradable film group was the same as that of black film group, the net income of the former would be higher than the latter.

In summary, not only did the fully biodegradable film have the advantage of environmentally friendliness, but also it can improve micro-ecological environment of soil to benefit crop growth and yield formation, in comparison with conventional plastic film. Due to its merits of natural degradation and environmental protection, it would be a potential substitute for conventional plastic film and contribute to the construction of environmentally friendly ecosystem.

From the perspectives of the extent of acceptance by the farmers, it is critical to analyse the economic output to input ratio, and the net economic income under the RFM system in this study. The socio-economic aspects of the RFM farming system are presented in Table 2. There were significant differences in the economic profitability between RFM farming system and CK over two growing seasons. Generally, total input in three mulching film treatments proved to be much higher than that of CK, due to additional labour and material expenditure in the RFMs treatments, including constructing the ridge-furrow system, as well as conducting mulching.

We also quantitatively estimated the output to input ratio. It was obvious that the lowest output-input ratio was in CK, and the highest ratio was in RFMT treatment across two growing seasons, which was approximately 16 % higher than the ratio of RFMD (Table 2). This was primarily because the fully biodegradable film was more expensive than the transparent plastic film. In addition, straw mulching was easily operated in field, which required lower labour input than film mulching, based on our field records about the employed farmers. Therefore, total economic input was generally lowered in RFMG treatment than that of other mulching treatments. As reported previously, the RFMD treatment displayed similar effects as the RFMT and RFMB treatments, such as reducing soil moisture loss, collecting rainwater, and producing a higher yield and economic output (Xiaoli et al., 2012). In particular, we had also conducted a social survey on the attitudes of local farmers towards the recognition and adoption by local farmers and crop growers in terms of the RFMD farming system (data not shown). In general, local farmers were highly positive and showed strong willing to extend the RFMD farming technology to their farmlands. The survey results showed that RFMD could be implemented in the same manner as the RFMT and RFMB by farmers and therefore brought relatively high economic benefits to them.

On the other hand, RFMT appeared to be the most efficient if the economic factor was solely considered. The only question derived from the survey was that plastic sheet product for agronomic use and its recovery or reuse were temporarily unavailable in local market. In this study, plastic residues had been clearly removed by hand after crop harvest, although the residues were frequently considered to be a source of pollution in the field. This should not be a question if definite measures were strictly taken, while plastic residue pollution caused a wide range of controversy in northwest China (Yan et al., 2006). Alternatively, the RFMD practice showed a relatively high economic profitability and would be a favourite choice for local farmers, due to its outstanding environmental friendliness. In summary, the RFMD farming system appeared to be an optimal farming practice to boost maize productivity and profitability in the semiarid Kenya. In coming years, the application and demonstration of RFMD system in Kenya would provide a window of opportunity for smallholder farmers, because this system can significantly reduce soil erosion and increase field productivity as well as economic income.

We also performed the principal component analysis (PCA) on the related parameters. The PCA decomposed 29 indicators of 5 treatments in two growing seasons into 2 principal components (Fig. 4). The results showed that cumulative variance contribution rate of PCA1 was 98.4 %, and that of PCA2 was 1.2 %, respectively. Fig. 4 indicated the compositional indicators closely related to yield and water use efficiency, including grain yield, aboveground biomass, aboveground biomass water use efficiency (WUE_A), ear length, plant height, ear weight, leaf area, row number per ear, cob diameter, cob weight, number of kernel per ear, kernel weight per ear 100-grain weight, grain output, hay yield output, total income, total output and net income. These parameters can be defined as the related indicators of yield formation and economic income. Furthermore, the ΔSWS storage (changes in soil water), evapotranspiration (ET) and bare tip length indicators were identified as the indicators of water consumption. Each treatment in two growing seasons was found to share the same location regularity in the PCA figure. This suggested that the variation trend for all the treatments remained the same in two growing seasons. The location of RFMD16 and RMFB16 in the PCA figure was in close proximity, indicating that the performance of two treatments proved to be similar in 2016 and the same in 2017.

Since the growing season in 2017 was more arid than that of 2016, RFMD2017 and RMFB2017 locations were closer in the PCA figure than RFMD2016 and RMFB2016 location, suggesting that the gap between the RFMD and RFMB treatments was smaller in the drier growing season (Fig. 4). In conclusion, the fully biodegradable film mulching was not only environmentally friendly but also had the merits of increasing field productivity and economic income, maintaining moisture, suppressing evapotranspiration and increasing temperature. The performance of RFMT2016, RFMD2016 and RFMB2016, representing transparent film mulching treatment, fully biodegradable film mulching treatment and black film mulching treatment in 2016, can be more explained by yield index, when compared with RFMT2017, RFMD2017 and RFMB2017, which represented the corresponding treatments in 2017. FP2016 and RFMG2016, representing flat plant and grass mulching treatment in 2016, can be more effectively explained by water consumption index, when compared with FP2017 and RFMG2017, which represented the same treatments in 2017.

4. Conclusion

We first introduced the RFMD farming system to EAP, since this system was appropriate and accepted for smallholder farmers. The RFMD solution demonstrated a few significant advantages in improving field productivity, soil water conservation and economic harvest, comparing with local conventional flat planting. Particularly, it showed obvious advantages in environmental friendliness and sustainability at the field scale, and at the same time it harvested as high as 96 % grain yield of RFMT, a relatively high output. Importantly, from the environmentally friendly perspective, the RFMD farming system displayed great potential to guarantee maize production and food security in EAP or even across the whole semiarid Africa. Finally, the plastic film products for agronomic use are currently not available in local market, and the recycling and utilization of plastic residues also prove to be a key obstacle which needs to be properly resolved in EAP. Therefore, the fully degradable film mulching might be a promising farming solution to boost rainfed maize production and environmental sustainability in east African Plateau.

CRediT authorship contribution statement

Xiao-Feng Zhang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Chong-Liang Luo:** Data curation, Investigation, Software, Writing - original draft. **Hong-Xu Ren:** Investigation, Resources, Writing - review & editing. **Run-Zi Dai:** Data curation, Methodology. **David Mburu:** Resources, Writing - review & editing. **Levis Kavagi:** Resources, Writing - review & editing. **Kiprotich Wesly:** Writing - review & editing. **Aggrey B. Nyende:** Resources, Writing - review & editing. **Asfa Batool:** Writing - review & editing. **You-Cai Xiong:** Conceptualization, Formal analysis, Funding acquisition, Project administration, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2020.126124.

References

Arnhold, S., Ruidisch, M., Bartsch, S., et al., 2013. Simulation of runoff patterns and soil erosion on mountainous farmland with and without plastic-covered ridge-furrow cultivation in South Korea. Trans. ASABE 56, 667–679. https://doi.org/10.13031/2013.42671.

Bhardwaj, R.L., 2013. Effect of mulching on crop production under rainfed condition - a review. Agric. Rev. 34, 188. https://doi.org/10.5958/j.0976-0741.34.3.003.

Chakraborty, D., Nagarajan, S., Aggarwal, P., et al., 2008. Effect of mulching on soil and plant water status, and the growth and yield of wheat (*Triticum aestivum* L.) in a semi-arid environment. Agric. Water Manag. 95, 1323–1334. https://doi.org/10.1016/j.agwat.2008.06.001.

Conway, G., Toenniessen, G., 2003. Science for African food security. Sci. 299, 1187–1188. https://doi.org/10.1126/science.1081978.

Han, J., Jia, Z.K., Han, Q.F., Zhang, J., 2013. Application of mulching materials of rainfall harvesting system for improving soil water and corn growth in northwest of China. J. Integr. Agric. 12, 1712–1721. https://doi.org/10.1016/S2095-3119(13)60342-1.

Jia, Y., Li, F.M., Wang, X.I., et al., 2006. Soil water and alfalfa yields as affected by alternating ridges and furrows in rainfall harvest in a semiarid environment. Field Crops Res. 97, 167–175. https://doi.org/10.1016/j.fcr.2005.09.009.

Kasirajan, S., Ngouajio, M., 2012. Erratum to: polyethylene and biodegradable mulches for agricultural applications: a review. Agron. Sustain. Dev. 32, 501–529. https://doi.org/10.1007/s13593-011-0068-3.

Li, C., Moore-Kucera, J., Lee, J., Corbin, A., Brodhagen, M., Miles, C., Inglis, D., 2014. Effects of biodegradable mulch on soil quality. Appl. Soil Ecol. 79, 59–69. https://doi.org/10.1016/j.apsoil.2014.02.012.

Liu, C.A., Jin, S.L., Zhou, L.M., Jia, Y., Li, F.M., Xiong, Y.C., Li, X.G., 2009. Effects of plastic film mulch and tillage on maize productivity and soil parameters. Eur. J. Agron. 31, 241–249. https://doi.org/10.1016/j.eja.2009.08.004.

Li, F.M., Guo, A.H., Wei, H., 1999. Effects of clear plastic film mulch on yield of spring wheat. Field Crops Res. 63, 79–86. https://doi.org/10.1016/S0378-4290(99)00027-1.

Li, X.Y., Gong, J.D., Gao, Q.Z., Li, F.R., 2001. Incorporation of ridge and furrow method of rainfall harvesting with mulching for crop production under semiarid conditions. Agric. Water Manag. 50, 173–183. https://doi.org/10.1016/S0378-3774(01)00105-6.

Mckee, G.W., 1964. A coefficient for computing leaf area in hybrid corn. Agron. J. 56, 240–241.

Mo, F., Wang, J.Y., Xiong, Y.C., Nguluu, S.N., Li, F.M., 2016. Ridge-furrow mulching system in semiarid Kenya: a promising solution to improve soil water availability and maize productivity. Eur. J. Agron. 80, 124–136. https://doi.org/10.1016/j.eja.2016.07.005.

Moreno, M.M., Moreno, A., 2008. Effect of different biodegradable and polyethylene mulches on soil properties and production in a tomato crop. Sci. Hortic. 116, 256–263. https://doi.org/10.1016/j.scienta.2008.01.007.

Muthuri, C.W., Ong, C.K., Black, C.R., Ngumi, V.W., Mati, B.M., 2005. Tree and crop productivity in *Grevillea*, *Alnus* and *Paulownia*-based agroforestry systems in semi-arid Kenya. For. Ecol. Manage. 212, 23–39. https://doi.org/10.1016/j.foreco.2005.02.059.

Otake, Y., Kobayashi, T., Asabe, H., 1995. Murakami N. and Ono K., Biodegradation of low-density polyethylene, polystyrene, polyvinyl chloride, and urea formaldehyde resin buried under soil for over 32 years. J. Appl. Polym. Sci. 56, 1789–1796. https://

doi.org/10.1002/app.1995.070561309.

Ohtake, Y., Kobayashi, T., Asabe, H., Murakami, N., 1998a. Studies on biodegradation of LDPE—observation of LDPE films scattered in agricultural fields or in garden soil. Polym. Degrad. Stab. 60, 79–84. https://doi.org/10.1016/S0141-3910 (97)00032-3.

Ohtake, Y., Kobayashi, T., Asabe, H., Murakami, N., Ono, K., 1998b. Oxidative degradation and molecular weight change of LDPE buried under bioactive soil for 32-37 years. J. Appl. Polym. Sci. 70, 1643–1648. https://doi.org/10.1002/(SICI)1097-4628(19981128)70:9<1643::AID-APP1>3.0.CO;2-V.

Pelleschi, S., Rocher, J.P., Prioul, J.L., 1997. Effect of water restriction on carbohydrate metabolism and photosynthesis in mature maize leaves. Plant Cell Environ. 20, 493–503. https://doi.org/10.1046/j.1365-3040.1997.d01-89.x.

Ran, X.H., Deng, P.Y., Zhuang, Y.G., Dong, L.S., Gao, G., Zhao, C., Liu, F., 2003. Characterization of full-biodegradable starch-PVA-polyester film. Chem. Res. Chin. Univ. 19, 249–252. https://doi.org/10.1007/BF02974893.

Shah, A.A., Hasan, F., Hameed, A., Ahmed, S., 2008. Biological degradation of plastics: a comprehensive review. Biotechnol. Adv. 26, 246–265. https://doi.org/10.1016/j.biotechadv.2007.12.005.

Wang, J.Y., Mo, F., Nguluu, S.N., Zhou, H., Ren, H.X., Zhang, J., Kariuki, C.W., Gicheru, P., Kavaji, L., Xiong, Y.C., Li, F.M., 2016. Exploring micro-field water-harvesting farming system in dryland wheat (*Triticum aestivum* L.): an innovative management for semiarid Kenya. Field Crops Res. 196, 207–218. https://doi.org/10.1016/j.fcr.2016.07.001.

Wanjogu, S.N., Kamoni, P.T., 1986. Kenya Soil Survey. Soil conditions of Juja Estate (Kiambu District). Republic of Kenya, Ministry of Agriculture, National Agricultural Laboratories, Kenya Soil Survey, Nairobi.

Witt, U., Einig, T., Yamamoto, M., Kleeberg, I., Deckwer, W.D., Muller, R.J., 2001. Biodegradation of aliphatic-aromatic copolyesters: evaluation of the final biodegradability and ecotoxicological impact of degradation intermediates. Chemosphere 44, 289–299. https://doi.org/10.1016/S0045-6535(00)00162-4.

Xiaoli, C., Pute, W., Xining, Z., Xiaolong, R., Zhikuan, J., 2012. Rainfall harvesting and mulches combination for corn production in the subhumid areas prone to drought of China. J. Agron. Crop Sci. 198, 304–313. https://doi.org/10.1111/j.1439-037X.2012.00508.x.

Yan, C., He, W., Turner, N.C., 2014a. Plastic-film mulch in Chinese agriculture: importance and problems. World Agricult. 4, 32–36.

Yan, C.R., Liu, E.K., Shu, F., Liu, Q., Liu, S., He, W.Q., 2014b. Review of agricultural plastic mulching and its residual pollution and prevention measures in China. J. Agric. Resources Environ 31, 95–102.

Yan, C.R., Mei, X.R., He, W.Q., Zheng, S.H., 2006. Present situation of residue pollution of mulching plastic film and controlling measures. Trans. Chin. Soc. Agric. Eng. (Transactions of the CSAE) 22, 269–272. https://doi.org/10.3321/j.issn:1002-6819.2006.11.055.

Yao, Z., Zheng, X., Liu, C., Lin, S., Zuo, Q., Butterbach-Bahl, K., 2017. Improving rice production sustainability by reducing water demand and greenhouse gas emissions with biodegradable films. Sci. Rep. 7, 39855. https://doi.org/10.1038/srep39855.

Zhao, H., Wang, R.Y., Ma, B.L., Xiong, Y.C., Qiang, S.C., Wang, C.L., Liu, C.A., Li, F.M., 2014. Ridge-furrow with full plastic film mulching improves water use efficiency and tuber yields of potato in a semiarid rainfed ecosystem. Field Crops Res. 161, 137–148. https://doi.org/10.1016/j.fcr.2014.02.013.

Zhao, L., Tsuchiya, K., Inoue, Y., 2004. Fully-biodegradable poly(3-hydroxybutyrate)/poly(vinyl alcohol) blend films with compositional gradient. Macromol. Biosci. 4, 699–705. https://doi.org/10.1002/mabi.200400009.

Zhou, L.M., Jin, S.L., Liu, C.A., Xiong, Y.C., Si, J.T., Li, X.G., Gan, Y.T., Li, F.M., 2012. Ridge-furrow and plastic-mulching tillage enhances maize-soil interactions: opportunities and challenges in a semiarid agroecosystem. Field Crops Res. 126, 181–188. https://doi.org/10.1016/j.fcr.2011.10.010.