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Agronomic performance of polyethylene and biodegradable plastic film mulches in a maize cropping system in a humid continental climate

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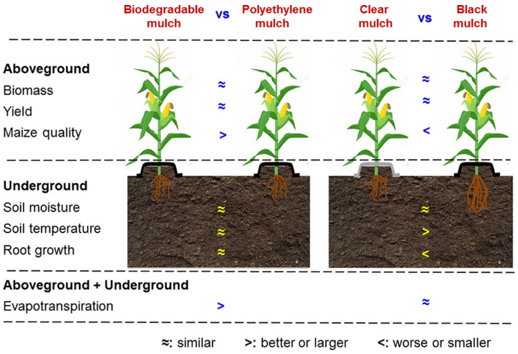
HIGHLIGHTS

- Maize yield was similar between biodegradable and polyethylene films.
- Soil temperature and root structure were also similar between the two types of films.
- Maize quality was best for black biodegradable plastic mulches.
- Clear mulches increased soil temperature, while black mulches sometimes decrease it.
- Maize root growth was inhibited by clear mulch.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic polyethylene mulch has been widely used in crop production, but also causes environmental pollution if plastic residues accumulate in soil. Biodegradable plastic mulches (BDM) are a potential solution to problems caused by polyethylene mulches, as BDMs are designed be tilled into the soil after the growing season and then biodegrade. However, the agronomic performance of BDMs still needs to be tested for comparison to polyethylene mulch. We carried out a two-year field experiment in 2018 and 2019 in a typical humid continental climate in Northeast China. Maize was planted in a ridge-furrow pattern, with mulching treatments consisting of no mulch (control), clear BDM, black BDM, clear polyethylene, and black polyethylene. Clear mulches increased soil temperature when compared to no mulch control treatments, while black mulches decreased or did not change soil temperature during the early growing season. Soil temperature and root morphology were similar between BDM and polyethylene mulches for a given type of plastic color. Maize yield did not differ across all the treatments. Maize protein, fat, N and P contents were generally higher for black BDM than other treatments, suggesting that maize quality benefited especially from black BDM. Overall, these results show that, in a humid continental climate, the agronomic performance of clear and black BDMs was equivalent to, or better than, that of polyethylene plastic mulches for maize production.

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1. Introduction

Plastic film mulching is widely applied in agriculture across various climates, soils, and seasons (Subrahmaniyan and Mathieu, 2012). Plastic film mulching can provide numerous benefits, such as increase soil temperature and moisture (Ding et al., 2019), improve crop water use efficiency (Zhou et al., 2009), reduce weed and pest pressure (Jones, 1991; Qin et al., 2018), minimize the development time for seed and fruit (Wang et al., 2007; Subrahmaniyan and Zhou, 2008), reduce herbicide and fertilizer use (Martín-Closas et al., 2017), prevent soil erosion, and consequently improve crop yield and quality (Greer and Dole, 2003). Plastic film mulching is an important by indispensable global agricultural management for food safety. A recent meta-analysis of 3160 observations shows that plastic film mulching on average increased crop yield by 24% (Gao et al., 2019). The global use of agricultural much films is expected to grow by a compound annual growth rate (CAGR) of 7.4% between 2018 and 2026, with the major market shares in the Asia-Pacific region (48.6%), followed by Europe, North-America, Middle East and Africa, and Latin America (*Transparency Market Research*, 2018).

Most plastic mulches are made of polyethylene, which is highly stable under a wide range of environmental conditions. The longevity of polyethylene plastic film far exceeds the crop growth cycle (Subrahmaniyan and Mathieu, 2012). This type of plastic mulch film cannot always be completely removed from the fields after harvest, leading to accumulation of plastic residues in the soil, which in turn can negatively impact soil health and crop growth (Xiao and Zhao, 2005; Gao et al., 2019). A potential alternative to polyethylene film is biodegradable mulch (BDM) film, which can be converted into nontoxic compounds such as carbon dioxide or methane, and microbial biomass by microbial metabolism (Sintim and Flury, 2017; Sander, 2019). Thus, BDMs are more ecologically sustainable than polyethylene films (Kapanen et al., 2008; Anzalone et al., 2010), as soil pollution due to accumulation of plastic residues can be avoided (Barragán et al., 2016).

To be a viable alternative, BDMs need to fulfill the same agronomic functions of traditional polyethylene films (Moreno and Moreno, 2008). Some studies report that BDMs and polyethylene films have similar effects on soil temperature (Liu et al., 2011; Li et al., 2016) and crop yield (Zhang et al., 2010; Ghimire et al., 2018; Hayes et al., 2019). Conversely, other studies show that BDMs do not reach the extent of soil warming achieved by polyethylene (Schettini et al., 2007; Moreno and Moreno, 2008), as BDMs have lower solar transmittance (Schettini et al., 2007). Moreover, BDMs may fragment before harvest and affect soil temperatures (Saglam et al., 2017). Uncertainty about agronomic performance is a key factor for farmers hesitating to adopt BDM mulches over polyethylene mulches. Therefore, BDMs need to be tested for their agronomic performance as compared with polyethylene mulches.

Plastic mulch films often come in two versions: (1) black and opaque, and (2) clear and translucent (Lament, 1993). Black mulches are more effective for weed control, but typically provide less soil warming than clear mulch (Ashworth and Harrison, 1983). Black mulches are reported to produce larger maize yield than clear ones (Qin et al., 2018), smaller yields (Mbah et al., 2010), or no difference between yields (Mo et al., 2017b). The influence of mulch color on crop yield is highly specific, and may vary with climate and seasonal conditions (Moreno and Moreno, 2008). Currently, little information exists on how black and clear BDM and polyethylene differ in terms of crop yield and quality.

In this study, we conducted a two-year field experiment in a temperate maize agro-ecosystem with five mulching treatments (no mulch, clear BDM, black BDM, clear polyethylene, and black polyethylene) in Northeast China. We measured soil properties (temperature, moisture, bulk density, soil organic carbon and total nitrogen), root morphological indices (weight, length, surface area, volume, diameter), and maize yield, biomass and quality (starch, protein, fat, and nutrient elements) in 2018 and 2019. Our objectives were to (1) to determine the effects of BDM and polyethylene mulches on soil temperature and maize growth performance for black and clear mulches, and (2) to quantify the effects on maize yield and quality. We hypothesized that BDMs would have similar agronomic performance as compared with polyethylene mulches.

2. Materials and methods

2.1. Site and experimental design

The experimental site is located in Haicheng county (40°58′42”N, 122°43′41″E), Liaoning Province, China. The site has a humid continental climate, with a mean annual temperature of 10.4 °C and a mean annual precipitation of 721 mm. The average frost-free period is 166 days. Mean monthly temperatures and precipitation during the experimental years are shown in Fig. S1. The cropping system consists of monoculture maize (*Z. mays* L.) with conventional tillage management. The soil is a Meadow Soil according to the Chinese Soil Taxonomy, and had a soil organic carbon content of 11.3 g kg^{-1}, bulk density of 1.14 g cm^{-3}, and pH of 5.1 in the 0–20 cm depth before the experiment started.

A randomized block design experiment with four replicates was initiated in the spring of 2018. Each block had five treatments: No mulch, Clear biodegradable mulch (Clear BDM), Black biodegradable mulch (Black BDM), Clear polyethylene mulch (Clear polyethylene), and Black polyethylene mulch (Black polyethylene). Each plot had an area of 86.4 m^2 (12 m long × 7.2 m wide). Ridges (20 cm high, 60 cm wide) were shaped by a ridge plough pulled by a tractor at the end of April. Fertilizers and maize seeds were simultaneously placed into the soil on the ridges 3 cm apart by a combined sowing and fertilizing machine. Subsequently, atrazine was sprayed as herbicide in each plot (not used in 2019). Then, the entire surface (all ridges and furrows) was covered with mulch films and holes were cut manually after seedling emergence to allow plants to grow out of the plastic films. Planting and harvest dates, as well as fertilizer and seed information are given in Table S1.

The BDM consisted of polybutyleneadipate-*co*-terephthalate (PBAT) and polylactic acid (Fig. S2) and was obtained from BASF (Ecovio® M2351); and had a thickness of 8 μm and a density of 1.38 g cm^{-3}. The polyethylene film was obtained from a local company and had a thickness of 8 μm. The width of all mulch rolls was 110 cm. After crop harvest, polyethylene film was removed from the field manually, while the BDM was tilled into soil.

2.2. Field sampling and measurements

2.2.1. Soil temperature and moisture

Soil temperature and moisture were measured during the entire maize growing seasons in 2018 and 2019. Soil temperature was measured every 2 h by a DS1923 iButton® temperature/humidity logger (Maxim Integrated, San Jose, CA, USA). At each plot, one logger was put at 5 cm and 25 cm depth soil before mulching in spring. In autumn, the loggers were removed. Soil moisture at 10 cm depth was measured in situ between 9 am and 10 am once in every two weeks with a moisture probe (Trime ®-Pico 64/32, IMKO GmbH, Ettlingen, Germany).

2.2.2. Biomass, yield, and crop quality

In autumn of 2018 and 2019, corn plants in the center 5 m of the center two rows, were cut off in each plot. The number and total fresh weight of harvested ears (with husks) and stalks were recorded. Five ears and one stalk were randomly selected and brought to the laboratory where fresh weight was recorded, and then dried in the oven at 60 °C to constant weight to measure moisture contents. The fresh weight of harvested ears and corresponding moisture were then used to calculate yield. The 100-seed weight and the length of the maize cob were recorded. Organic compounds (crude starch, crude protein, crude fat), minerals (ash content) and nutrient elements (nitrogen, phosphorus, potassium, calcium, magnesium, iron, manganese, copper, and zinc) in maize kernels were measured to estimate maize quality. Crude starch was determined by acid hydrolysis (Wang and Copeland, 2015), crude protein by the Kjeldahl method (FOSS Kjeltec™ 8100) (DIN EN ISO 3188, 1978), and crude fat by Soxhlet extraction (ISO 6492, 1999). Ash content was determined gravimetrically after combustion (BS ISO 5984, 2003). Nitrogen was determined by the Kjeldahl method (FOSS Kjeltec™ 8100) (DIN EN ISO 3188, 1978), phosphorus by the spectrophotometric method (DIN ISO 3946, 1982), potassium by flame emission photometry (ISO 7485, 2000), and calcium, magnesium, iron, manganese, copper, and zinc by atomic absorption spectrophotometry (BS EN ISO 6869, 2001).

After maize harvest, two plant roots in each plot were randomly sampled by digging up the soil adjacent to the main trunk up to a radius of 40 cm and a depth of 60 cm. The roots were washed with water to remove soil, then cut into sections, and measured by a root scanner (EPSON Expression 11000XL) and an image analyzer (EPSON Expression 11000XL) for root morphology, including total root length, total surface area, total volume, average diameter. Root specific surface area was calculated as to total surface area divided by total volume.

2.2.3. Soil parameters

The 0–20 cm soil layer soil was sampled with a 4-cm-diameter auger from the ridge edge in the middle of each plot. The soil samples were sieved (2 mm) to remove plant debris and gravel, air-dried at room temperature, and then ground. Soil pH was determined with an ion-selective electrode (DIN ISO 11263, 1996). Soil organic carbon (SOC) and total nitrogen (STN) were determined by dry combustion using a Vario El III Element Analyzer (Germany), soil available phosphorus (SAP) was measured spectrophotometrically (DIN ISO 11263, 1996).

To calculate the water use efficiency, soil water contents in 0–10, 10–20, 20–40, 40–60, 60–100 cm layers soil were measured before planting and after harvest in 2018 and 2019. Specifically, soil samples in these five layers were collected by an auger, packed into aluminum boxes, weighted and sealed with plastic wrap, and taken back to laboratory. Soil water content was calculated by the weight loss after the soil was oven dried at 105 °C to constant weight. Bulk density was measured for each soil layer using a home-made soil auger.

2.3. Evapotranspiration, water use efficiency, and thermal time calculations

Evapotranspiration (ET, mm) of water from the soil surface and plant leaves through the stomates (transpiration) was calculated from the soil water balance during the growing season of maize (Li et al., 2012):

$$ET = W_{\text{sowing}} - W_{\text{harvest}} + R \tag{1}$$

where, W_{sowing} (mm) and W_{harvest} (mm) are water storage in 0–100 cm soil horizon at sowing and at harvest, respectively, R (mm) is the rainfall during maize growing season. We assume here that there is no drainage during the growing season, because rainfall was too low to drain down below 1 m or cause surface runoff. Soil water storage was calculated from measured soil water contents and contents of respective soil depths.

Water use efficiency (WUE, kg ha^{-1} mm^{-1}) was calculated following the method in Doorenbos and Pruitt (1977):

$$\text{WUE} = Y/ET \tag{2}$$

where Y (kg ha^{-1}) is the dry yield of the crop.

Soil thermal time (τ) under different mulch treatments was calculated following the method in Campbell and Norman (1979):

$$\tau = \sum_{i=1}^{n} \left(\frac{T_{\max,i} + T_{\min,i}}{2} - T_{\text{base}} \right) \times \Delta t \tag{3}$$

where $T_{max,\ i}$ and $T_{min,\ i}$ are daily maximum and minimum soil temperatures at a given day i. n is the total number of days, Δt is the time increment of 1 day, and T_{base} is the base temperatures, which was set to 0 °C.

2.4. Statistical analysis

We assessed the effects of mulching on soil parameters, maize root characteristics, yield and quality parameters, and water use efficiency in each year using analysis of variance (ANOVA) with randomized block design. Mulch treatments and blocks were incorporated as fixed factors. The Duncan test was then used to compare the treatment differences for various variables. Correlation analyses were conducted to analyze the relationships between maize yield and quality parameters and thermal time and root characteristics. All the statistical analyses were performed using SPSS 22.0 package (SPSS, Chicago, IL) and the significance level was set as $\alpha = 0.05$.

3. Results

3.1. Soil temperature and moisture

Soil temperature differences between BDM and polyethylene mulches were apparent during the early growing season but faded in the late season (Fig. 1 a, b, c, d). Specifically, temperature at 5 cm depth soil was higher under BDM than under polyethylene mulches during early growing season (before June 10) in 2018 (Fig. 1 a). Black BDM had 1– 2 °C higher temperatures than black polyethylene, and clear BDM had at up to 1 °C higher temperatures than clear polyethylene. Similarly, temperature at 25 cm depth soil was higher under black BDM than under black polyethylene, but was similar under clear BDM and polyethylene (Fig. 1 b). In the middle of the growing season (from Jun 10 to Aug 1), temperatures at 5 cm and 25 cm depth soils were similar under BDM and polyethylene. In 2019, soil temperatures were similar between BDM and polyethylene across the whole growing season (Fig. 1 c and d). Soil moisture at 10 cm depth soil did not show significant differences between BDM and polyethylene, nor between clear and black mulches (Fig. S3).

Soil temperature differences between clear and black mulches in both 2018 and 2019 were most pronounced at the early growing season (before May 17), with temperatures between 2 and 5 °C higher under clear as compared to black mulches (Fig. 1 e, f, g, h). Temperature differences diminished, and then disappeared in the middle of in the growing season. In the late stage of the growing season (after Aug 1), the soil temperature in 5 cm depth was about 1 °C higher under clear polyethylene than under black polyethylene in 2018, other temperatures were similar between under clear and black mulches.

Similarly, soil temperature differences between plastic mulches and no mulch were generally apparent during early growing season but disappeared in the late season (Fig. 1 i, j, k, l). Specifically, in the early season (before June 10), clear mulches increased soil average temperature, up to 4 °C, but black BDM generally did not change soil temperature and black polyethylene even decreased temperature by 1 to 2.5 °C in 5 cm depth soil and by 0.5 to 1.5 °C in 25 cm depth soil in 2018. In the middle of the growing season (from Jun 10 to Aug 1), all the mulch treatments reduced daily mean temperature by about 1 °C (Fig. 1 i), and decreased its daytime temperature but increased night temperature, for 5 cm depth soil in 2018 (Fig. S4 and S5). In 2019, only black BDM decreased soil temperature (25 cm depth) while the other mulches generally did not change temperatures, and the contrasting mulching effects on daytime and night temperatures was not apparent (Fig. S4 and S5). Generally, all the mulch treatments reduced daily soil temperature amplitudes compared with no mulch (Fig. S6).

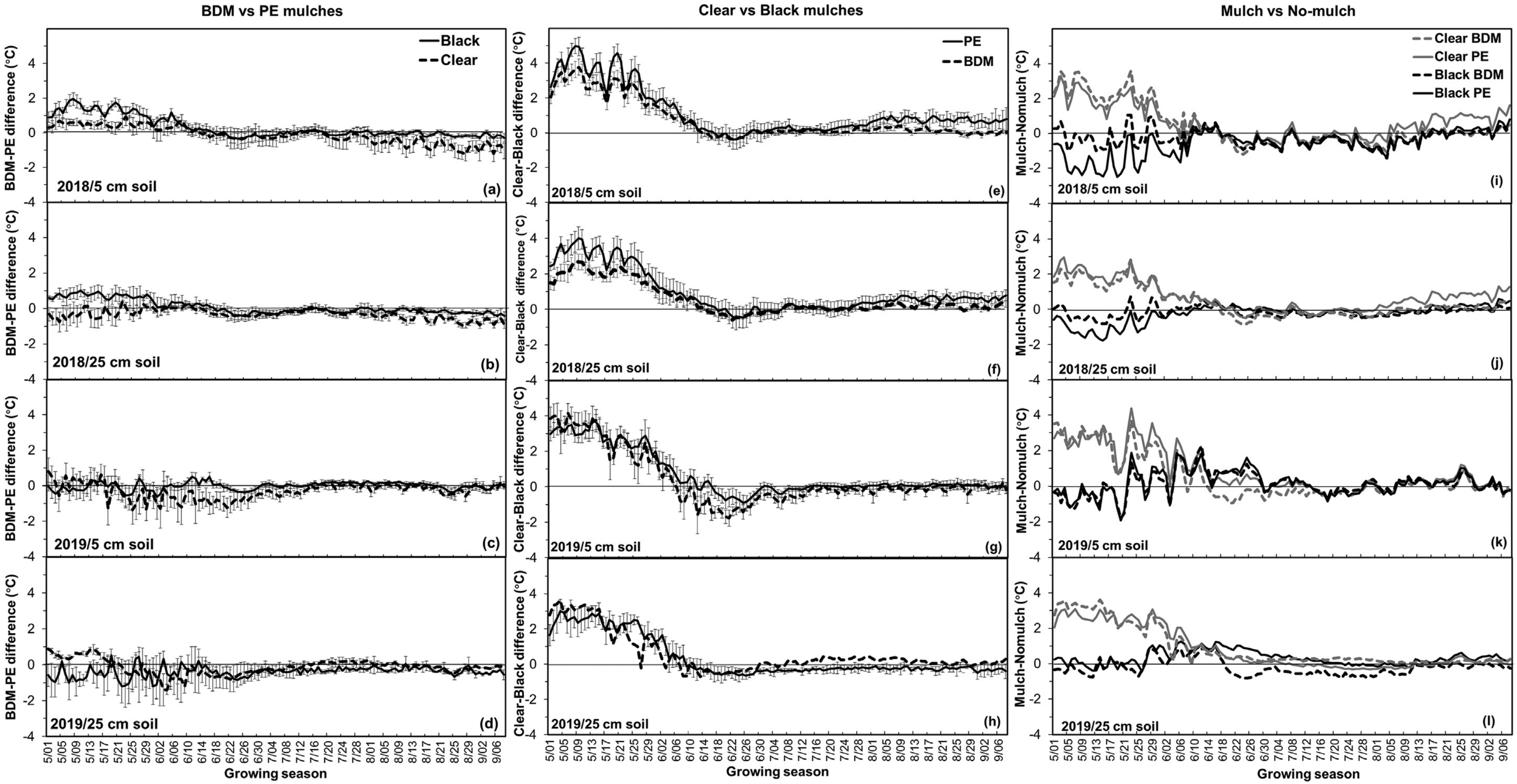

Fig. 1. Daily average temperature differences at 5 cm and 25 cm depth soil across 2018 and 2019 growing seasons between biodegradable plastic mulch (BDM) and polyethylene mulch (PE) (a, b, c, d, “Black” and “Clear” legends represent black BDM minus black PE and clear BDM minus clear PE, respectively), between clear and black mulches treatments (e, f, g, h, “PE” and “BDM” legends represent clear PE minus black one and clear BDM minus black BDM, respectively), and between mulches and no mulch treatments (i, j, k, l). The error bars denote standard errors ($n = 4$).

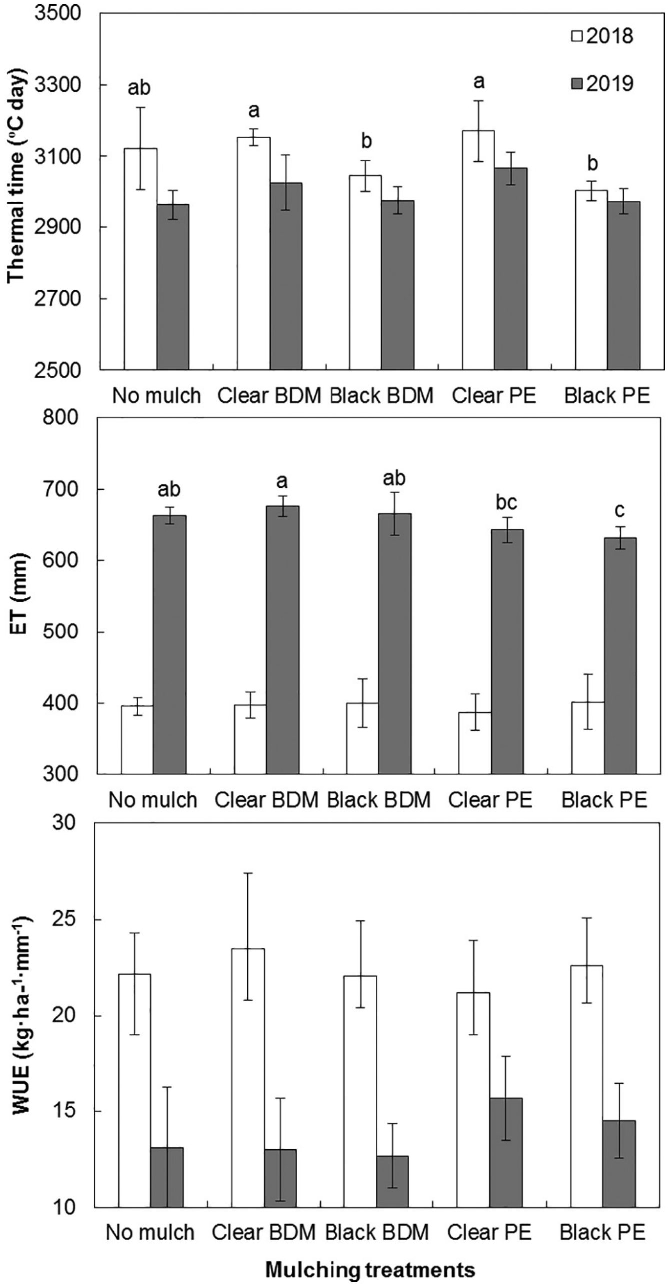

Fig. 2. Thermal time, evapotranspiration (ET) and maize water use efficiency (WUE) under different mulch treatments. The error bars show the standard deviations ($n = 4$). Different letters denote significant differences among mulch treatments at the 5% level and no letter indicates no significant differences.

3.2. Soil thermal time, evapotranspiration and water use efficiency

Following the trend of soil temperature, soil thermal time was generally significantly ($P = 0.016$) larger under clear mulches than under black mulches and no mulch treatments in 2018 (Fig. 2). Black mulches had a trend to reduce soil thermal time compared to no mulch in 2018, but not in 2019. Evapotranspiration (ET) was significantly ($P = 0.042$) different among mulch treatments in 2019 but not in 2018 (Fig. 2). In 2019, black and clear polyethylene reduced ET by 4.7% and 3% compared to no mulch, respectively, but other mulch treatments had no effect on ET. Water use efficiency (WUE) was not affected by mulch treatments both in 2018 and 2019. ET was higher in 2019 than in 2018, resulting in lower WUE in 2019 that in 2018.

Soil chemical properties (pH, SOC, total N and available P) did not differ significantly between different mulch treatments (Table S2). Bulk densities did not have significant differences among the mulch treatments in 2018, whereas in 2019, bulk density under clear polyethylene was 8.4%, 7.1%, and 8.4% ($P = 0.041$) lower than clear BDM, black BDM, and no mulch, respectively, and black polyethylene also had a lower bulk density than the three treatments. These results suggest that polyethylene mulches tend to reduce bulk density.

3.3. Maize root characteristics

Among all the maize root characteristics, only specific surface area was significantly ($P = 0.031$) different among the mulch treatments in 2018 (Table 1). Clear BDM and polyethylene significantly reduced root specific surface area by 11.5% and 15.4% compared to no mulch, respectively, but black mulches and no mulch showed no differences in 2018. Similarly, the mass, total length, and total volume of roots were lower under clear mulches than black mulches and no mulch, although the difference was not significant. In 2019, roots under black polyethylene had the largest mass, total length, total surface, and total volume among all the treatments.

3.4. Maize yield and biomass

Maize yield, straw mass, aboveground biomass, 100-seed weight, and spike length all did not differ among different mulch treatments, both for 2018 and 2019 (Table 2). The largest yield and aboveground biomass were found under clear BDM in 2018 but under clear polyethylene in 2019. The clear BDM increased yields above no mulch by 6.8% in 2018, and clear polyethylene increased yield by 16% in 2019. Straw mass and aboveground biomass were larger in 2019 than in 2018, for all the treatments.

3.5. Maize seed quality

Among all the organic compounds and nutrient elements in the maize kernels, only protein, fat, and N content in 2018 and only P content in 2019 were significantly different among mulch treatments (Table 3). Seed protein and N contents were significantly ($P = 0.033$, $P = 0.023$) higher under black BDM than under other mulches in 2018, which was also this case in 2019, though not significant. Seed fat content was 11% and 9.1% higher ($P = 0.029$) under black BDM and polyethylene compared to no mulch, respectively. In 2019, seed P content was also highest under black BDM, which was 33.3%, 27.3% and 16.7% higher ($P = 0.025$) compared with clear polyethylene, black polyethylene, and no mulch, respectively. Other seed quality indicators, including starch, potassium, magnesium, calcium, iron, manganese, copper and zinc, were similar among mulch treatments.

BDM: biodegradable mulch; PE: polyethylene mulch. The data show the mean ± stdev ($n = 4$). Different letters denote statistical significant differences at the 5% level and no letter indicates no significant differences.

3.6. Correlations among organic compounds in kernels, root characteristics, and thermal time

In 2018, root length, mass, surface area, volume, and root shoot ratio were negatively correlated with thermal time ($P < 0.05$ or $P < 0.01$, Fig. 3). Protein content in kernels had a positive correlation with root length ($r = 0.54$, $P < 0.05$), and fat content was positively correlated with root weight ($r = 0.45$, $P < 0.05$) and volume ($r = 0.51$, $P < 0.05$) in 2018. In 2019, there was no significant correlation among organic compound in seed, root properties, and thermal time.

Table 1
Root characteristics in different mulch treatments in 2018 and 2019.

Treatments	Mass (g·m^{-2})	Total length (m·plant^{-1})	Total surface area (cm^2·plant^{-1})	Total volume (cm^3·plant^{-1})	Average diameter (mm·plant^{-1})	Specific surface area (cm^2·cm^{-3})	Nitrogen (%)	Root:shoot ratio
2018								
No mulch	98 ± 22	98 ± 44	2168 ± 703	41 ± 10	0.77 ± 0.05	52 ± 3a	0.8 ± 0.3	0.05 ± 0.01
Clear BDM	88 ± 17	68 ± 18	1790 ± 436	39 ± 9	0.85 ± 0.03	46 ± 2bc	0.7 ± 0.1	0.04 ± 0.01
Black BDM	103 ± 41	92 ± 15	2180 ± 412	44 ± 10	0.80 ± 0.06	50 ± 3ab	0.8 ± 0.1	0.05 ± 0.02
Clear PE	76 ± 46	55 ± 12	1562 ± 477	37 ± 16	0.90 ± 0.10	44 ± 5c	0.8 ± 0.1	0.04 ± 0.02
Black PE	121 ± 7	88 ± 15	2269 ± 365	48 ± 9	0.84 ± 0.06	47 ± 3abc	0.7 ± 0.1	0.06 ± 0.01
2019								
No mulch	74 ± 22	56 ± 14	1930 ± 378	55 ± 13	1.13 ± 0.21	36 ± 6	0.7 ± 0.0	0.03 ± 0.01
Clear BDM	90 ± 8	73 ± 31	2269 ± 685	58 ± 13	1.04 ± 0.20	39 ± 7	0.7 ± 0.2	0.04 ± 0.01
Black BDM	69 ± 14	70 ± 24	1970 ± 360	46 ± 10	0.95 ± 0.22	44 ± 10	0.7 ± 0.1	0.03 ± 0.01
Clear PE	83 ± 26	65 ± 31	2034 ± 743	52 ± 14	1.05 ± 0.13	39 ± 5	0.7 ± 0.1	0.03 ± 0.01
Black PE	93 ± 35	90 ± 55	2613 ± 1195	63 ± 20	1.02 ± 0.21	40 ± 8	0.7 ± 0.1	0.04 ± 0.02

BDM: biodegradable mulch; PE: polyethylene mulch. The data show the mean ± stdev ($n = 4$). Different letters denote significant differences at the 5% level and no letter indicates no significant differences.

4. Discussion

Among all soil properties, soil temperature showed the most obvious change due to the mulch treatments, particularly during early growing season (Fig. 1). The diminishing effect on soil temperature at the middle growing season is supported by many other studies (Wang et al., 2007; Shen et al., 2011; Saglam et al., 2017). The reason is that the canopy formation of maize which provides sufficient shade to the soil surface in the middle growth stage, thereby reducing the effects of soil coverings, such as plastic mulches (Zhou et al., 2009). In the late growth stage, however, when the canopy shrinks due to the wilting of maize leaves, clear polyethylene had again higher soil temperature compared to no mulch (Fig. 1 i and j). BDM had a slightly higher soil temperature than polyethylene, especially for black mulches during the early season of 2018 (Fig. 1 a and b), but the two types of mulches had similar soil temperature in 2019 (Fig. 1 c and d). The thermal time was similar between BDM and polyethylene, both for black and clear mulches in 2018 and 2019 (Fig. 2). These results indicate that BDM containing PBAT/PLA provides equivalent soil heating compared to polyethylene.

Notably, we found that clear mulches increased soil temperature but black mulches decreased or did not change soil temperature during early growing season as compared to no mulch, and clear polyethylene had up to 5 °C higher temperatures at 5-cm depth than black polyethylene (Fig. 1). Accordingly, soil thermal time was significantly larger under clear mulches than under black mulches in 2018 (Fig. 2). The increased soil temperature under clear mulches was consistently reported previously (e.g. Iremiren and Milbourn, 2008; Zhao et al., 2012). The reason is that short-wave solar radiation can penetrate through the clear plastic film, while the long-wave radiation from the cannot pass through the plastic, and the condensation water on the plastic film further reduces the transmittance of long-wave infrared radiation (Yaduraju and Mishra, 2004). Black mulches have been reported to increase soil temperature (Subrahmaniyan and Zhou, 2008; Sun et al., 2018; Sintim et al., 2019), but also decreases (Mo et al., 2017a) have been reported. These mixed results likely are related to the degree of contact between the mulch film and the soil surface (Tarara, 2000). Black mulches have limited light transmittance, and most of the thermal energy from light is adsorbed by the mulches. If the mulch film has good contact with soil surface, the thermal energy on the black plastic can be better transferred to the soil through thermal conduction (Pramanik et al., 2015), thereby increasing soil temperature. If the mulches are not close enough to contact the soil surface, like in our study, it will lead to low thermal conductivity between mulch and soil surface, and much of the thermal energy absorbed by the black mulch is lost to the atmosphere.

Table 2
Maize yields, straw and aboveground biomass.

Treatments	Yield (Mg·ha^{-1})	100-seed mass (g)	Spike length (cm·plant^{-1})	Straw (Mg·ha^{-1})	Aboveground biomass (Mg·ha^{-1})
2018					
No mulch	8.8 ± 0.7	27 ± 3	17 ± 1	8.5 ± 1.3	19.4 ± 2.1
Clear BDM	9.4 ± 1.9	26 ± 1	16 ± 1	8.7 ± 2.3	20.2 ± 2.6
Black BDM	8.8 ± 0.8	29 ± 3	17 ± 1	8.4 ± 0.5	19.1 ± 1.1
Clear PE	8.2 ± 1.0	26 ± 2	16 ± 0	9.1 ± 2.3	19.1 ± 2.7
Black PE	9.1 ± 1.1	29 ± 1	17 ± 0	9.0 ± 2.1	19.8 ± 3.1
2019					
No mulch	8.7 ± 2.0	29 ± 4	17 ± 1	12.1 ± 3.0	22.5 ± 5.0
Clear BDM	8.8 ± 1.8	30 ± 4	17 ± 1	11.5 ± 3.2	22.0 ± 5.2
Black BDM	8.4 ± 1.2	31 ± 3	18 ± 1	11.7 ± 2.6	21.9 ± 4.3
Clear PE	10.1 ± 1.3	31 ± 5	18 ± 1	12.3 ± 1.5	24.8 ± 2.2
Black PE	9.2 ± 1.1	31 ± 4	17 ± 1	11.7 ± 2.0	22.8 ± 2.1

Aboveground biomass = Yield + Straw + cob +husk. BDM: biodegradable mulch; PE: polyethylene mulch. The data show the mean ± stdev ($n = 4$). Different letters denote significant differences at the 5% level and no letter indicates no significant differences.

Plastic mulch usually retains soil moisture by preventing evaporation (Hillel, 1982; Yang et al., 2015). Although evaporation was not measured directly in our study, we calculated the amount of soil evapotranspiration across the whole growing season based on the mass balance of soil water. We found that polyethylene was better in reducing soil evapotranspiration than BDM and no mulch treatments in 2018, while BDM and no mulch treatments had similar evapotranspiration (Fig. 2). Similar results were observed by Qiao et al. (2008). The reason is that BDMs began to break up and fragment in the middle and late stage of corn growth, and thus were not as effective in preventing evaporation. Nevertheless, this did not translate into significant differences for soil moisture between BDM and polyethylene (Fig. S3). In addition, clear and black mulches had similar evapotranspiration (Fig. 2), suggesting that color of mulch had limited influence on soil water cycling in our study. It has often been reported that plastic mulching will preserve soil moisture (Wang et al., 2009; Saglam et al., 2017), but this is mostly in regions where soil moisture limits crop growth. In our study, soil moisture was not a limiting factor, and therefore no benefit of plastic mulch film mulching was observed.

Root morphology is a key characteristic for the uptake of water and nutrients (Nagel et al., 2009). In our study, most root morphology characteristics were lower under clear mulches than under black mulches and no mulch in 2018, particularly the specific surface area (Table 1). The promotion of crop or vegetable root growth by black polyethylene film was also reported by Wolfe et al. (1989) and Pandey et al. (2015). We speculate that weed growth under clear mulches may have inhibited maize root growth. In contrast, black mulch can prevent

Table 3
Organic compounds and nutrient elements in maize seeds.

Treatments	Starch (%)	Protein (%)	Fat (%)	Ash (%)	N ($g \cdot kg^{-1}$)	P ($g \cdot kg^{-1}$)	K ($g \cdot kg^{-1}$)	Mg ($g \cdot kg^{-1}$)	Ca ($g \cdot kg^{-1}$)	Fe ($mg \cdot kg^{-1}$)	Zn ($mg \cdot kg^{-1}$)	Mn ($mg \cdot kg^{-1}$)	Cu ($mg \cdot kg^{-1}$)
2018													
No mulch	59 ± 7	7.7 ± 0.4ab	3.3 ± 0.1b	4.7 ± 1.6	12.4 ± 0.6ab	3.5 ± 0.2	4.4 ± 0.0	1.9 ± 0.1	1.7 ± 0.4	72 ± 39	24 ± 1	10.8 ± 1.5	4.4 ± 1.7
Clear BDM	61 ± 7	7.6 ± 0.2b	3.4 ± 0.2ab	4.6 ± 2.5	12.1 ± 0.4b	3.1 ± 0.3	4.4 ± 0.0	2.0 ± 0.1	1.8 ± 0.4	51 ± 14	23 ± 1	11.4 ± 1.5	4.0 ± 1.7
Black BDM	63 ± 6	8.0 ± 0.4a	3.7 ± 0.4a	6.9 ± 3.6	12.8 ± 0.7a	3.3 ± 0.1	4.4 ± 0.0	1.9 ± 0.1	1.7 ± 0.3	67 ± 33	23 ± 4	11.2 ± 1.6	3.8 ± 1.5
Clear PE	66 ± 4	7.5 ± 0.3b	3.4 ± 0.2ab	8.6 ± 3.1	12.0 ± 0.4b	3.1 ± 0.4	4.4 ± 0.0	1.9 ± 0.1	1.9 ± 0.3	89 ± 7	27 ± 3	11.9 ± 0.7	4.1 ± 1.2
Black PE	59 ± 10	7.7 ± 0.3b	3.6 ± 0.2a	6.0 ± 3.2	12.3 ± 0.5b	3.3 ± 0.3	4.4 ± 0.0	1.8 ± 0.1	1.9 ± 0.4	63 ± 23	22 ± 3	10.7 ± 0.2	3.8 ± 1.7
2019													
No mulch	61 ± 2	8.4 ± 0.7	2.8 ± 0.5	2.7 ± 1.1	13.6 ± 1.2	2.4 ± 0.4b	2.8 ± 0.2	0.9 ± 0.1	2.1 ± 0.3	27 ± 5	15 ± 1	5.8 ± 0.8	5.5 ± 1.0
Clear BDM	64 ± 3	7.7 ± 0.8	2.8 ± 0.2	2.4 ± 1.5	12.5 ± 1.3	2.5 ± 0.4ab	3.1 ± 0.4	0.9 ± 0.1	1.9 ± 0.6	25 ± 4	16 ± 2	5.5 ± 0.8	5.4 ± 1.1
Black BDM	62 ± 3	8.6 ± 0.8	3.0 ± 0.4	4.1 ± 1.7	13.9 ± 1.3	2.8 ± 0.2a	2.8 ± 0.1	0.9 ± 0.1	1.9 ± 0.6	27 ± 6	16 ± 2	5.6 ± 0.4	5.4 ± 1.1
Clear PE	61 ± 2	8.3 ± 1.1	3.1 ± 0.3	2.4 ± 1.2	13.4 ± 1.8	2.1 ± 0.1b	3.0 ± 0.3	0.9 ± 0.1	2.2 ± 0.1	27 ± 2	16 ± 3	6.1 ± 1.1	5.3 ± 1.1
Black PE	63 ± 2	8.1 ± 0.8	3.0 ± 0.3	1.9 ± 0.8	13.2 ± 1.2	2.2 ± 0.3b	2.8 ± 0.1	0.9 ± 0.1	2.0 ± 0.1	26 ± 2	15 ± 1	5.5 ± 0.1	5.6 ± 1.3

weeds from competing for nutrients with the roots of crops by limiting light transmittance, thus promoting the growth of crop roots (Rajablarijani et al., 2014). The reason for similar root growth under clear mulches and no mulch in 2019 was likely because no herbicides were used in 2019, resulting in similar weed growth between the two treatments. Under these circumstances, black polyethylene was best for weed control due to its complete soil coverage during the growing season, and thus had the largest root morphology indices (Table 1). Another reason may be related to the difference in soil temperature between the two differently colored mulches (Fig. 1), as negative correlations between root characteristics (root length, surface area, volume, root mass) and thermal time were observed (Fig. 3).

Although soil temperature and root morphology characteristics were affected by mulch treatments, maize yield did not differ significantly among the mulch treatments (Table 2). In dry climates, plastic mulching conserves soil moisture, which then translates into a yield advantage (Yin et al., 2017); while in more humid climates or when plants are being irrigated, the yield benefits of plastic mulch are mainly due to increased soil temperatures and weed suppression (Ghimire et al., 2018). A recent meta-analysis based on global data showed that the effect of film mulching on maize yield tend to be negligible, when the rainfall in the growing period exceeds 770 mm and the average air temperature in the growing period is more than 24 °C (Yu et al., 2018). Another recent meta-analysis based on the data from the Loess Plateau of China reported that plastic mulch did not increase maize yield at mean annual precipitation over 627.6 mm and mean annual temperature over 13.1 °C (Wang et al., 2020). Our experimental site had a mean annual temperature of 10.4 °C and a mean annual precipitation of 721.3 mm, with average air temperature of 23.5 °C and 22.5 °C and rainfall of 397 mm and 585 mm in the growing season in 2018 and 2019, respectively (Fig. S1), which are close to the above threshold values. Ma et al. (2007) also found no apparent effects of plastic mulching on maize yield in our investigated region based on a model that relates yield increment under mulching and accumulated temperature in Northeast China. Thus, plastic mulching does not appear to provide yield benefits for maize in a humid continental climate provided weeds are sufficiently controlled by herbicides.

Unlike yield, some maize quality indices were responsive to mulch treatments. Protein, fat, and N and P contents were generally all higher for black BDM than other treatments (Table 3), suggesting that maize quality benefited from black BDM in our investigated region. Gupta and Acharya (1993) also found that crops covered with black mulch had better nutrient uptake than those covered with clear mulch, which was explained by black mulch promoting root growth. In our study, root characteristics were also generally more expressed under black mulches than clear mulches (Table 1), corroborating this explanation. Moreover, seed protein content was positively correlation with root length ($r = 0.54$, $P < 0.05$), and fat content was positively correlated with root mass ($r = 0.45$, $P < 0.05$) and volume ($r = 0.51$, $P < 0.05$) (Fig. 3). It remains unclear though why black BDM was superior to black polyethylene in terms of seed quality while they had similar root characteristics. We speculate that this may be due to somewhat lower, but not significant, maize yield under the former mulch than the latter (Table 2). Higher yield will have a dilution effect for plant nutrient contents, e.g., N and P (Ding et al., 2019), thereby also impacting protein and fat. Fan et al. (2019) also observed slightly better nutrient contents in maize under BDM than under polyethylene, but lower yield under the former treatment.

5. Conclusions

Here we show that the agronomic performance including soil moisture and temperature, root growth, and maize yield of both clear and black BDMs were equivalent to clear and black polyethylene mulches for maize production in a humid continental climate. A recent meta-analysis where the agronomic performance of BDMs

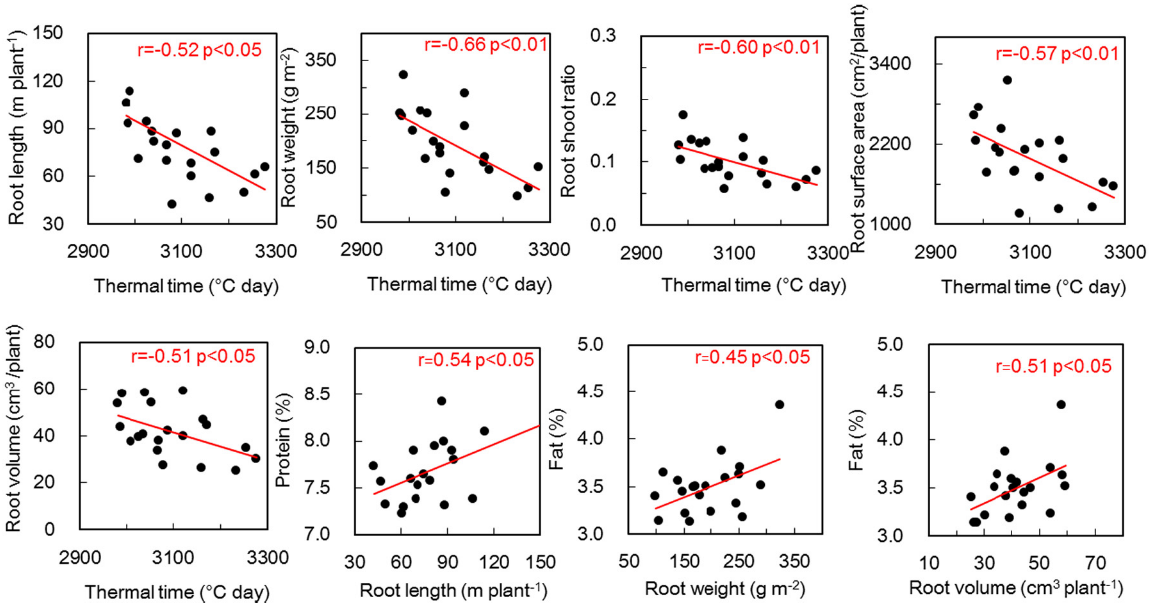

Fig. 3. Correlations between organic compound in maize kernels, root characteristics, and thermal time in 2018.

against polyethylene mulch was assessed also found that, while differences in soil temperature and weed suppression may exist, crop yields are usually not affected (Tofanelli and Wortman, 2020). In our study, BDMs even showed some benefits over polyethylene mulches: Protein, fat, and N and P contents in seeds were generally all higher for black BDM than other treatments. We conclude that BDM consisting of by PBAT/PLA is equivalent to polyethylene mulch film in terms of yield in a humid continental climate, where soil moisture is not a limiting factor for maize production.

CRediT authorship contribution statement

Zhengyu Wang: Investigation, Formal analysis, Writing- Original draft preparation.

Mingxuan Li: Investigation, Formal analysis.

Markus Flury and **Sean M. Schaeffer**: Conceptualization, Writing-Reviewing and Editing.

Yi Chang, **Zhao Tao**, **Zhaojie Jia**, **Shitong Li**: Investigation.

Fan Ding: Conceptualization, Methodology, Formal analysis, Data Curation, Writing- Reviewing and Editing.

Jingkuan Wang: Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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