Effects of Plastic Film Residue on Tomato Growth During Seedling and Flowering-Fruit Setting Stages (Postprint)

Authors: Zou Xiaoyang, Niu Wenquan, Liu Jingjing, Li Yuan, Guan Yahui, Liang Bohui, Guo Lili, Zhang Mingzhi

Date: 2017-11-07T00:00:00+00:00

Abstract

Plastic film residue pollution has become a significant factor threatening farmland ecosystems, not only hindering soil water and nutrient transport, but also affecting crop growth. To elucidate the influence patterns of plastic film residue on tomato growth at different growth stages, a plot experiment method was employed, establishing six different plastic film residue levels of 0 kg • hm 2, 80 kg • hm 2, 160 kg • hm 2, 320 kg • hm 2, 640 kg • hm 2, and 1 280 kg • hm 2 to investigate the effects of plastic film residue amount on root characteristics, above-ground growth, and dry matter accumulation in tomato at the seedling stage and flowering-fruit setting stage, and the Logistic growth model was used to quantitatively analyze the effects of plastic film residue on the initial, peak, and late stages of tomato nutrient accumulation. The results showed that plastic film residue hindered root growth in tomato at both the seedling stage and flowering-fruit setting stage, with root volume, root length density, and root dry mass density all decreasing with increasing plastic film residue amount; with increasing plastic film residue amount, plant height and stem diameter at both the seedling and flowering-fruit setting stages showed decreasing trends, and the growth rates of plant height and stem diameter gradually declined. The initial and peak stages of tomato nutrient accumulation advanced with increasing plastic film residue amount, and the optimal timing for tomato topdressing should also be advanced. At both the seedling and flowering-fruit setting stages of tomato, the dry matter mass of roots, stems, flowers, and young fruits all decreased with increasing plastic film residue amount, while the dry matter mass of leaves showed an increasing trend. The inhibitory effects of plastic film residue on root growth, above-ground growth, and dry matter accumulation in tomato were greater at the seedling stage than at the flowering-fruit setting stage. Thus, it can be concluded that the damage caused by plastic film residue to tomato at the seedling stage was more severe than at the flowering-fruit setting stage, and both the initial and peak stages of dry matter accumulation advanced with increasing plastic film residue amount; strengthening water and fertilizer management during the tomato seedling stage and advancing the timing of water and fertilizer application are beneficial measures for mitigating the hazards of plastic film residue.

Full Text

Effect of Residual Plastic Film on Tomato Growth at Seedling and Blooming-Fruit Setting Stages

ZOU Xiaoyang[1], NIU Wenquan[1], LIU Jingjing[2], LI Yuan[3], GUAN Yahui[1], LIANG Bohui[2], GUO Lili[2], ZHANG Mingzhi

[1]Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China
[2]College of Water Conservancy and Architectural Engineering, Northwest A&F University, Yangling 712100, China
[3]Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China
Henan Province Water Conservancy Research Institute, Zhengzhou 450002, China

Abstract

Residual plastic film pollution has become a critical factor harming farmland ecosystems, not only impeding soil water and nutrient transport but also affecting crop growth. To elucidate the effects of residual plastic film on tomato growth across different developmental stages, a plot experiment was conducted with six residual plastic film levels: 0, 80, 160, 320, 640, and 1,280 kg·hm ^{2}. The study examined impacts on root characteristics, above-ground growth, and dry matter accumulation during the seedling and blooming-fruit setting stages, and employed Logistic growth models to quantitatively analyze how residual film affects the onset, peak, and end phases of tomato nutrient accumulation. Results showed that residual plastic film hindered root growth during both stages, with root volume, root length density, and root dry weight density decreasing as residual film amount increased. Plant height and stem diameter showed decreasing trends with increasing residual film, and their growth rates gradually declined. The onset and peak phases of tomato nutrient accumulation occurred earlier with higher residual film amounts, indicating that optimal fertilization timing should be advanced. During both stages, dry matter accumulation in roots, stems, flowers, and young fruits decreased with increasing residual film, while leaf dry matter showed an increasing trend. The inhibitory effects of residual plastic film on root growth, above-ground development, and dry matter accumulation were more pronounced during the seedling stage than during blooming-fruit setting. These findings demonstrate that residual plastic film causes greater damage during the seedling stage, and that both the onset and peak of dry matter accumulation advance with increasing residual film. Enhanced water and fertilizer management during the seedling stage and earlier application of water and nutrients are effective measures to mitigate residual film damage.

Keywords: Tomato; Root; Dry matter accumulation; Growth parameter; Residual plastic film

Introduction

Plastic mulching offers benefits such as soil temperature increase, moisture conservation, salinization suppression, pest and weed control, and soil improvement, making it an essential agricultural production material. The technology has been applied to over 40 crops including cotton, grains, melons, fruits, and tea, driving significant advances in agricultural productivity and transforming production practices. However, plastic film can persist in soil for 200–400 years, with residual amounts increasing with mulching duration. As plastic film usage and mulching area continue to grow in China, the hazards of residual film to agroecosystems intensify annually, becoming a bottleneck restricting sustainable agricultural development. Investigations reveal that residual film in soil consists primarily of small fragments (<4 cm^{2}) with stratified distribution, with over two-thirds concentrated in the 0–10 cm surface layer. Residual film not only disrupts soil pore continuity and reduces water flow cross-sectional area, thereby impeding water and nutrient transport, but also obstructs crop root growth, causing malformed root systems that appear "chicken-claw" or "cluster" shaped, ultimately affecting crop development.

The presence of residual plastic film in soil inevitably hinders crop growth and development. Xie et al. found that wheat (*Triticum aestivum* L.) yield decreased by 0.8%-22.1%, maize (*Zea mays* L.) grain yield by 2.1%-27.5%, and cotton (*Anemone vitifolia* Buch.) yield by 1%-7.5% as residual film amount increased. Dong et al. reported that at 1,000 kg • hm ^{2} residual film, cotton yield decreased by 13.5%-18.1%, seedling survival rate dropped by 13.0%-21.1%, and biomass, root surface area, and root-shoot ratio all significantly declined. Gao et al. observed that residual film reduced maize emergence rate, delayed emergence time, and restricted root elongation, subsequently affecting above-ground growth. Xin et al., based on field experiments, found that maize emergence rate decreased with increasing residual film, with the most significant impacts occurring during the seedling and jointing stages. However, most previous research has focused on effects at crop maturity, particularly on yield, plant height, and stem diameter, while few studies have examined impacts across different growth stages.

Crop root systems, above-ground parts, and dry matter accumulation respond differently to residual film at various developmental stages. Understanding these differential responses can identify critical periods requiring enhanced field management, thereby effectively mitigating residual film damage. Numerous studies have analyzed crop responses to specific factors at different growth stages to develop appropriate management practices. For example, Han et al. investigated the effects of corn straw strip mulching on potato growth during early and mid-to-late developmental stages, finding significant promotion of dryland potato growth. Cui et al. studied the effects of water deficit at different growth stages on pear-jujube (*Zizyphus jujube* Mill.) quality, discovering that moderate water deficit during fruit maturation improved quality. However, research on how residual film affects crops at different growth stages remains limited. Therefore, this study established different residual film levels to analyze effects on tomato (*Lycopersicon esculentum* Miller) root characteristics, above-ground growth, and dry matter accumulation during the seedling and blooming-fruit setting stages, revealing differential impacts across growth stages and providing a theoretical basis for developing appropriate field management strategies in residual film-contaminated areas.

Materials and Methods

1.1 Experimental Site and Materials The experiment was conducted from October 2, 2015, to January 22, 2016, in a solar greenhouse (108°04 E, 34°20 N, altitude 521 m) at the China Institute of Water-Saving Agriculture for Arid Regions, Northwest A&F University, Yangling, Shaanxi Province. The experimental area has a warm temperate semi-arid and semi-humid climate, with annual total radiation of 475.8 kJ · m ^{2}, annual sunshine of 2,163.8 h, frost-free period of 221 days, mean annual temperature of 13°C, and annual evaporation of approximately 1,400 mm. The greenhouse had a gable roof structure oriented north-south (13.5 m long × 6.5 m wide × 3.8 m ridge height). During the tomato growth period, the average temperature and humidity in the greenhouse were 21.82°C and 50.72%, respectively. The experimental soil was sandy clay loam. In the 0–50 cm soil layer, clay particles (<0.001 mm) accounted for 15.3%, silt particles (0.001-0.05 mm) for 62.1%, and sand particles (0.05–2 mm) for 22.6%. Soil pH was 7.23, electrical conductivity was 0.24 dS · m ^{1}, initial gravimetric water content was 20.16% (measured by oven-drying method), and bulk density was 1.36 g · cm ^{3} (measured by ring knife method). Soil total nitrogen, alkali-hydrolyzable nitrogen, organic matter, total potassium, and available phosphorus contents were 0.88 g · kg ^{1}, 32.51 mg · kg ^{1}, 7.67 g · kg ^{1}, 22.3 g · kg ^{1}, and 12.87 mg · kg ^{1}, respectively, indicating moderate soil fertility.

The tomato variety 'Haidi' was used. Seedlings were raised in plug trays on September 12, 2015, and transplanted on October 2, 2015 (20 days after sowing) with uniform growth vigor. The experimental plot [Figure 1: see original paper] had a total area of 75.6 m^{2} (6.0 m × 12.6 m), divided into six equal experimental zones (1.0 m × 12.6 m) by soil ridges (10 cm high, 1,260 cm long, 10 cm wide at top, 20 cm wide at bottom). Each zone was further divided into three micro-plots (1.0 m × 4.2 m) as three replicates. Waterproof canvas was buried

50 cm deep along both sides of the ridges to prevent water and fertilizer infiltration between plots and root entanglement. Plant spacing was 60 cm, with six uniformly vigorous seedlings planted in each micro-plot, totaling 18 plants per treatment. Before transplanting, base fertilizer was applied at rates of 200 kg · hm ^{2} nitrogen (N content 46.4%), 150 kg · hm ^{2} phosphorus (P content 12%), and 300 kg · hm ^{2} potassium (KCl content 24%). Sufficient water for seedling establishment was applied two days before transplanting. Water-soluble fertilizer (Fengdeli, containing 20% total N, 20% total P, 20% total K, and 0.5% trace elements) was used during the seedling and blooming-fruit setting stages. The tested thin white plastic film had a thickness of 0.008 mm, tensile load 2.7 N, nominal strain at break 300 N, right-angle tear load 1.4 N, and total ash content 0.5%, with low tensile load to simulate easily breakable residual film in fields.

1.2 Experimental Design Most residual film in soil consists of small fragments (<4 cm^{2}). To eliminate effects of fragment shape and size on root growth, this study uniformly used rectangular residual film pieces measuring 1 cm × 2 cm. Previous research has established a linear relationship between residual film amount Mf (kg · hm ^{2}) and mulching years X (a): $M\text{f} = 5.546X + 47.840$ ($R^2 = 0.871$). Based on this equation, six residual film gradients were established to predict long-term mulching effects: 0, 80, 160, 320, 640, and 1,280 kg · hm ^{2}, corresponding to approximately 0, 6, 20, 49, 107, and 222 years of mulching, designated as T0, T1, T2, T3, T4, and T5, respectively. Field layout and replicates are shown in [Figure 1: see original paper].

Required base fertilizer and residual film for each plot were thoroughly mixed using a YJB4 mobile mixer (Jiangyin Yonghong Chemical Machinery Co., Ltd.) at 100 r · min ^{1} for 30 minutes. The mixture was then evenly spread in each plot. The tomato growth period was divided according to FAO-56 standards: seedling stage (October 2–November 20, 2015) and blooming-fruit setting stage (November 20, 2015–January 22, 2016). During growth, each plant received 2 L of water every 4 days, with 4 g of water-soluble fertilizer added to the irrigation water every 8 days, applied at the plant base. Weeding and pest control were performed promptly, with other management practices consistent with local customs. At the end of each stage, three uniformly vigorous tomato plants were selected from each micro-plot (nine plants per treatment) for root characteristic and dry matter accumulation analysis.

1.3 Measurement Methods

1.3.1 Soil Gravimetric Water Content Measurement Two days after each irrigation, soil samples were collected with an auger at 0–10, 10–20, 20–30, and 30–40 cm depths. Six sampling points per treatment were located between plants [Figure 1: see original paper]. Fresh soil mass was measured after placing samples in aluminum boxes, then oven-dried at 105°C. Gravimetric water content was calculated as: (fresh soil mass - dry soil mass) / dry soil mass × 100%.

1.3.2 Root Sampling and Measurement At the end of the seedling stage (November 20, 2015) and blooming-fruit setting stage (January 22, 2016), root samples were extracted using the trench method. Centered on each plant, a soil volume of 0.064 m^3 (40 cm long × 40 cm wide × 40 cm deep) was excavated from the 0-40 cm layer. Root samples were washed with low-pressure water to remove debris. After drying surface moisture with filter paper, roots were scanned by layer (0-10, 10-20, 20-30, and 30-40 cm) using an EPSON Perfection V700 Photo scanner at 300 dpi. Scanned images were analyzed using WinRHIZO software to obtain root length and volume parameters.

1.3.3 Plant Height and Stem Diameter Measurement Tomato plant height and stem diameter were measured before transplanting using a tape measure and digital caliper. After establishment, measurements were taken every 7 days. Plant height was measured from the plant base near the soil surface, and stem diameter was measured at the main stem base using a digital caliper.

1.3.4 Dry Matter Accumulation Measurement At the end of each growth stage, sample plants were separated into roots, stems, leaves, flowers, and young fruits. Samples were killed at 105°C for 30 minutes, then oven-dried at 80°C to constant weight. Dry weights of each organ were measured using an electronic balance (precision 0.01 g).

1.3.5 Calculation of Root Dry Weight Density and Root Length Density Root dry weight density (Dm) and root length density (Dl) were calculated using the formulas:

$$D_m = \frac{W}{V}$$

$$D_l = \frac{L}{V}$$

where Dm is root dry weight density in the 0-40 cm layer (g · m ^{3}), Dl is root length density in the 0-40 cm layer (m · m ^{3}), W is root dry weight in the 0-40 cm layer (g), V is soil volume in the 0-40 cm layer (0.064 m^3), and L is root length in the 0-40 cm layer (cm).

1.4 Logistic Growth Model Growth models are widely used to describe and predict biological development and economic characteristics. Most crop growth follows a Logistic model with an S-shaped curve suitable for describing various crop development processes. The model expression is:

$$y = \frac{K}{1 + ae^{-bt}}$$

where y is the estimated value of tomato growth indices, K is the maximum possible value of each index, a is the initial growth state parameter, b is the growth rate coefficient, e is the base of natural logarithms, and t is development time (days).

According to Logistic equation principles, the first derivative gives the tomato growth rate function $GR(t)$:

$$GR(t) = \frac{Kabe^{-bt}}{(1 + ae^{-bt})^2}$$

When $t = \ln(a)/b$ and $y = K/2$, the tomato growth rate GR reaches its maximum value MGR:

$$MGR = \frac{Kb}{4}$$

The second derivative yields:

$$\frac{d^2GR(t)}{dt^2} = \frac{Kab^2e^{-bt}(ae^{-bt} - 1)}{(1 + ae^{-bt})^3}$$

Setting this equal to 0 gives two inflection points t and t:

$$t_1 = \frac{\ln a - 1.317}{b}, \quad t_2 = \frac{\ln a + 1.317}{b}$$

When tomato growth rate GR reaches its maximum, development time t is denoted as $t\text{max} = \ln(a)/b$. The three key time points $t$max, t, and t represent the beginning, peak, and end phases of tomato nutrient accumulation, respectively. The period 0-t is the gradual increase phase, t-t is the rapid increase phase, and t to maturity is the slow increase phase. Nutrient use efficiency and growth rate are highest at $t$max. Therefore, enhanced water and fertilizer management at t and $t$max can achieve high and stable tomato yields.

1.5 Data Processing and Analysis Microsoft Excel 2010 was used for graphing, Origin Pro 9.0 for function fitting, Curve Expert 1.3 for Logistic model fitting, AutoCAD 2009 for experimental plot diagrams, and SPSS 19.0 for variance analysis and multiple comparisons (LSD method).

Results

2.1.1 Root Volume Results on the effects of different residual film amounts on tomato root volume at seedling and blooming-fruit setting stages [Figure 2: see original paper] showed that during the seedling stage, no significant differences were observed among treatments with 320 kg · hm ^{2} residual film ($F = 0.73$, $P > 0.05$). However, root volume with 640 kg · hm ^{2} residual film was significantly lower than other treatments ($F = 4.94$, $P < 0.05$). Compared with T0, root volume in residual film treatments decreased by 0.35%, 0.99%, 1.92%, 3.20%, and 4.17% during the seedling stage. During the blooming-fruit setting stage, root volume decreased with increasing residual film, with residual film treatments showing reductions of 0.03%, 0.17%, 0.25%, 0.69%, and 0.97% compared with the control. The reduction rate in root volume during the blooming-fruit setting stage was significantly lower than during the seedling stage ($F = 5.56$, $P < 0.05$), indicating that residual film had a stronger inhibitory effect on root growth during the seedling stage.

2.1.2 Root Length Density As shown in [Figure 3: see original paper], root length density during the seedling stage decreased by 2.59%, 6.94%, 9.16%, 15.85%, and 24.67% in residual film treatments compared with the control. During the blooming-fruit setting stage, root length density decreased by 1.82%, 5.29%, 8.21%, 13.85%, and 17.57%. The reduction rate in root length density was higher during the seedling stage than during the blooming-fruit setting stage, indicating stronger inhibition of root length growth during the seedling stage. During the seedling stage, root length density with 320 kg · hm ^{2} residual film was significantly lower than other treatments ($P < 0.05$). During the blooming-fruit setting stage, root length density showed a significant decreasing trend with increasing residual film at 160 kg · hm ^{2} ($F = 29.20$, $P < 0.05$). Root length density decreased with increasing residual film during both stages because surface soil residual film blocked water infiltration, causing most water to evaporate as ineffective water, reducing soil available water content and limiting root growth.

2.1.3 Root Dry Weight Density During the seedling stage, no significant differences in root dry weight density were observed among treatments with 160 kg · hm ^{2} residual film ($F = 1.69$, $P > 0.05$). However, at 1,280 kg · hm ^{2}, root dry weight density was significantly lower than other treatments ($F = 13.11$, $P < 0.05$). During the blooming-fruit setting stage, significant reductions occurred with 640 kg · hm ^{2} residual film ($F = 31.12$, $P < 0.05$). Root dry weight density decreased with increasing residual film during both stages, with reductions of 2.29%, 8.67%, 17.44%, 23.92%, and 31.59% during the seedling stage, and 1.72%, 6.52%, 13.14%, 17.75%, and 24.17% during the blooming-fruit setting stage. The differences in reduction rates between stages were 0.57%, 2.15%, 4.30%, 6.17%, and 7.42%, all positive values that increased with residual film amount [Figure 4: see original paper]. This indicates that residual film had a stronger inhibitory effect on root biomass accumulation during the seedling stage than during the blooming-fruit setting stage, with the inhibitory effect intensifying as residual film amount increased.

2.2.1 Effects of Residual Film on Plant Height and Stem Diameter

Effects of different residual film levels on tomato plant height and stem diameter are shown in [Figure 5: see original paper]. At the end of the seedling stage, plant height in residual film treatments decreased by 1.47%, 6.62%, 8.75%, 15.84%, and 24.11% compared with T0, with reduction rates increasing with residual film amount. At the end of the blooming-fruit setting stage, plant height in residual film treatments was 0.94, 0.93, 0.75, 0.67, and 0.59 times that of T0, decreasing with increasing residual film. Stem diameter at the seedling stage end decreased by 5.73%, 16.41%, 38.55%, 45.04%, and 57.63% compared with T0, while at the blooming-fruit setting stage end, it decreased by 1.97%, 6.90%, 13.14%, 23.11%, and 30.45%. Both plant height and stem diameter decreased with increasing residual film during both stages.

Plant height growth rate was negatively correlated with residual film amount [Figure 5c: see original paper]. During the seedling stage, plant height growth rate in residual film treatments decreased by 0.99%, 10.60%, 14.24%, 23.51%, and 34.77% compared with T0, with significant reductions at 640 kg · hm ^{2} ($P < 0.05$). During the blooming-fruit setting stage, plant height growth rate decreased by 6.28%, 7.01%, 43.96%, 48.55%, and 59.18% compared with T0, with T5 showing significantly lower growth rate than other treatments ($F = 11.25$, $P < 0.05$). Plant height growth rate decreased with increasing residual film during both stages. Maximum stem diameter growth rates during seedling and blooming-fruit setting stages were 0.328 mm · week ^{1} and 0.443 mm · week ^{1}, respectively, while minimum values were 0.139 mm · week ^{1} and 0.258 mm · week ^{1}. Stem diameter growth rate decreased with increasing residual film during both stages [Figure 5d: see original paper]. These results demonstrate that residual film inhibition of above-ground growth intensified with increasing residual film amount.

Tomato plant height (cm) and stem diameter (mm) were fitted using the Logistic growth model, with results shown in .

TABLE:1 Logistic model fitting parameters for tomato plant height and stem diameter under different residual film treatments

Treatment	Logistic Model Fitting Parameters	Maximum Growth Index (K)	Initial Status Parameter (a)	Growth Rate Coefficient (b)	Coefficient of Determination (R^2)	Maximum Growth Rate (MGR)	Beginning Period (t)	Peak Period (t_max)	End Period (t)
	Plant height								

Treatment	Logistic Model Fitting Parameters	Maximum Growth Index (K)	Initial Status Parameter (a)	Growth Rate Coefficient (b)	Coefficient of Determination (R^2)	Maximum Growth Rate (MGR)	Beginning Period (t)	Peak Period (t_max)	End Period (t)
	Stem diameter								

All treatments showed determination coefficients $R^2 > 0.87$, indicating that tomato plant height and stem diameter during both stages followed the Logistic growth model. Parameter K decreased with increasing residual film, suggesting that maximum achievable plant height decreased with more residual film. Parameter a decreased with increasing residual film, indicating that residual film hindered early plant growth. Parameter b, the growth rate coefficient, gradually decreased with increasing residual film, and maximum growth rate MGR also showed a decreasing trend, demonstrating that tomato growth vigor weakened as residual film amount increased.

The time points $t$max, t , and t represent the beginning, peak, and end phases of nutrient accumulation. For plant height, $t$max in residual film treatments occurred 1.29, 2.91, 5.94, 8.27, and 12.35 days earlier than T0, indicating that the beginning phase of nutrient accumulation advanced with increasing residual film. Compared with T0, t decreased by 4.67%, 16.18%, 29.81%, 39.63%, and 57.46%, showing that the peak nutrient accumulation phase also advanced. Parameter t showed a decreasing then increasing trend, decreasing with residual film at 160 kg·hm ^{2}. For stem diameter, both $t$max and t decreased with increasing residual film, indicating that both the beginning and peak phases of nutrient accumulation advanced. The optimal period for enhanced water and fertilizer management is at $t$max and t . These results demonstrate that as residual film amount increases, both the beginning and peak phases of nutrient accumulation advance, so the optimal fertilization time should be adjusted earlier accordingly.

2.2.2 Effects of Residual Film on Dry Matter Accumulation As shown in [Figure 6a: see original paper], dry matter accumulation during the seedling stage decreased with increasing residual film, with total dry matter in residual film treatments decreasing by 1.48%, 5.37%, 10.74%, 18.26%, and 27.11% compared with T0. No significant differences in root, stem, and leaf dry matter were observed among treatments with 160 kg·hm ^{2} residual film ($P > 0.05$). At 320 kg·hm ^{2}, stem dry matter significantly decreased with increasing residual film ($F = 19.87$, $P < 0.05$), while leaf dry matter showed no clear decreasing trend ($F = 1.45$, $P > 0.05$). Root and stem dry matter decreased with increasing residual film, while leaf dry matter gradually increased during the seedling stage.

During the blooming-fruit setting stage, dry matter accumulation was negatively correlated with residual film amount [Figure 6b: see original paper]. Dry matter at 160 $\text{kg}\cdot\text{hm}^{2}$ was significantly lower than other treatments ($F = 66.145$, $P < 0.05$). Total dry matter accumulation in residual film treatments decreased by 1.24%, 4.04%, 7.75%, 11.53%, and 18.37% compared with T0. The reduction rate in total dry matter accumulation during the blooming-fruit setting stage was lower than during the seedling stage, indicating that residual film had a stronger inhibitory effect on dry matter accumulation during the seedling stage. During the blooming-fruit setting stage, dry matter in roots, stems, flowers, and young fruits decreased with increasing residual film, while leaf dry matter showed an increasing trend.

Discussion

3.1 Effects of Residual Film on Tomato Root Growth As an exogenous material in soil, residual film blocks soil water transport channels, reduces soil porosity and aeration, impedes water infiltration and lateral diffusion, and causes soil compaction. Being highly flexible, residual film easily wraps around crop roots, hindering gas exchange between soil and atmosphere, deteriorating soil hydrothermal conditions, weakening microbial decomposition and mineralization, and affecting nutrient absorption and respiration.

This study found that tomato root volume, root length density, and root dry weight density all decreased with increasing residual film amount. During the seedling stage, gravimetric water content in the 0–10 cm layer increased with residual film amount [Figure 7: see original paper]. Higher surface soil moisture content worsened soil aeration, causing CO accumulation that hindered root aerobic respiration and consumed existing organic assimilates, thereby restricting root growth. Zhang et al. found that O concentration in paddy surface soil decreased with increasing water content, causing CO accumulation that hindered rice root growth. Cook et al. reported that soil water content significantly affected soil porosity and permeability, with high water content causing CO accumulation that inhibited aerobic microbial activity and root respiration, threatening crop growth. Thus, residual film primarily affects root growth by altering soil moisture conditions, root respiration, and soil hydrothermal conditions.

Soil moisture is closely related to root and above-ground growth. Correlation analysis between gravimetric water content in different soil layers and tomato growth indices showed that 0–10 cm water content was extremely significantly negatively correlated with tomato growth indices ($P < 0.01$), indicating that higher surface water content under residual film conditions was detrimental to tomato growth. This study found that as residual film amount increased, 0-10 cm water content gradually rose [Figure 7: see original paper], while root volume, root length density, and root dry weight density decreased. This occurred because residual film, mostly distributed in the surface layer, blocked water infiltration into deeper layers, concentrating water in the 0–10 cm layer. Under strong atmospheric evaporation, irrigation water became ineffective, causing physiological drought that hindered root growth. Kuster et al. and Wang et al. found that large ineffective evaporation from the surface layer adversely affected root growth, reducing root length, surface area, and volume.

Root growth also depends on water content in the root zone. Tomato roots are mainly distributed in the 10–40 cm layer, where water content was significantly positively correlated with all growth indices ($P < 0.05$) , clearly promoting root growth. Average water content in the 10–40 cm layer in residual film treatments decreased by 0.10%, 0.26%, 0.42%, 0.60%, and 0.73% compared with T0, indicating that root zone water content decreased with increasing residual film. Root zone water content plays a decisive role in root growth, with tomato roots adjusting structure and spatial distribution in response to water content changes. Xue et al. found that 0–80 cm water content decreased with reduced spring irrigation, significantly decreasing wheat root dry weight density, root length density, and root volume density. Ding et al. studied effects of 0–40 cm water deficit on peanut root growth during mid-to-late stages, finding that root length density, surface area, and volume all decreased with lower soil water content.

This study also found that residual film had stronger inhibitory effects on root volume, root length density, and root dry weight density during the seedling stage than during the blooming-fruit setting stage. The seedling stage is the most sensitive period to soil moisture, with weaker root penetration ability, while roots during the blooming-fruit setting stage have stronger water absorption and penetration capabilities. Seedling roots are mainly distributed in the 0–10 cm layer, where water content decreases with increasing residual film, hindering root growth. Ma et al. found that reduced surface layer water content decreased crop root stele area and vessel diameter, causing irregular vessel walls and reducing root length, diameter, and biomass. Residual film not only affects water distribution but also blocks soil pores, increasing resistance to root penetration. The area of blocked pores increases with residual film amount, reducing root living space and increasing growth resistance. Roots during the blooming-fruit setting stage have better vitality and growth capacity than during the seedling stage, making residual film effects less severe during the seedling stage. Therefore, enhanced water and fertilizer management during the tomato seedling stage is needed to mitigate residual film effects.

3.2 Effects of Residual Film on Above-Ground Growth and Dry Matter Accumulation

Above-ground growth is closely related to root growth, with reasonable root structure being the physiological basis for high yield and quality. This study found that plant height, stem diameter, and dry matter accumulation during both stages decreased with increasing residual film amount because root volume, root length density, and root dry weight density decreased, weakening water and nutrient absorption and reducing water transport to above-ground parts. This decreased leaf relative water content and chlorophyll content, weakening photosynthesis and affecting above-ground growth and dry matter accumulation. Liu et al. found that adding solid materials to soil increased root penetration resistance, increasing average root diameter and lateral water transport resistance, while accelerating endodermis lignification and suberization, reducing root hydraulic conductivity and causing mild water deficit that affected above-ground growth.

Above-ground growth and dry matter accumulation also relate to soil water content. Average water content in the 0–40 cm layer across treatments was (21.859±0.878)%, (21.787±0.794)%, (21.676±0.680)%, (21.570±0.583)%, (21.494±0.477)%, and (21.470±0.477)% [Figure 7: see original paper], decreasing with increasing residual film and causing water deficit in residual film treatments. Water deficit degree increased with residual film amount, gradually increasing total stomatal density and closed stomata number while decreasing stomatal aperture, causing CO deficit and weakening photosynthesis, thereby reducing dry matter accumulation. Water deficit caused by residual film also led to abscisic acid (ABA) accumulation in roots, affecting leaf stomatal aperture, reducing root water uptake, and inhibiting tomato growth and assimilate synthesis and accumulation. Photosynthetic products form the basis of dry matter; water deficit reduces leaf chlorophyll content and antioxidant enzyme activities, shortens functional periods of leaves and stems, weakens photosynthesis, and hinders product accumulation and transport, reducing dry matter accumulation. Under residual film conditions, root zone water content decreased with increasing residual film, accelerating leaf starch hydrolysis, causing sugar accumulation, slowing photosynthate transport, and creating carbon source imbalance between respiration and photosynthesis, leading to reduced plant height, stem diameter, and dry matter accumulation.

This study also found that leaf dry matter increased with residual film amount. This occurred because soil water content decreased with increasing residual film, and tomato growth is sensitive to water deficit. Residual film promoted ABA synthesis in roots, which was transported to above-ground parts to regulate growth and matter allocation, achieving optimal growth under water deficit, reducing growth redundancy, and balancing leaf and stem growth, thereby increasing leaf area and dry matter. This experiment used periodic irrigation, subjecting tomatoes to multiple rewatering cycles that enhanced compensatory growth effects, increasing leaf mass and area and allocating more dry matter to leaves. Wang et al. found that after multiple rewatering cycles, malondialdehyde and proline contents decreased while leaf area and biomass increased temporarily.

Conclusions

1) Tomato root volume, root length density, and root dry weight density all decreased with increasing residual film amount. Residual film had

stronger inhibitory effects on root growth during the seedling stage than during the blooming-fruit setting stage, warranting enhanced water and fertilizer management during the seedling stage.

2) Plant height and stem diameter during both stages decreased with increasing residual film amount, and their growth rates showed decreasing trends. The Logistic growth model effectively simulated tomato growth with residual film 1,280 kg·hm ^{2}. Both the beginning and peak phases of nutrient accumulation advanced with increasing residual film, so optimal fertilization timing should be adjusted earlier.
3) Total dry matter during both stages decreased with increasing residual film amount. Dry matter in roots, stems, flowers, and young fruits decreased with increasing residual film, while leaf dry matter showed an increasing trend. Residual film had stronger inhibitory effects on dry matter accumulation during the seedling stage than during the blooming-fruit setting stage. Enhanced water and fertilizer management during the seedling stage is necessary to mitigate residual film damage.

References

[1] Gong X W, Li X Y, Shi H B, et al. The interplanting between tomato and maize of soil temperature dynamics under mulched drip irrigation[J]. Acta Ecologica Sinica, 2015, 35(2): 489-496

[2] Yang S Y, Jiang C J. Effect of straw and plastic film mulching on warming and insulation of tea plantation in winter[J]. Chinese Journal of Eco-Agriculture, 2010, 18(2): 327-333

[3] Yan C R, Mei X R, He W Q, et al. Present situation of residue pollution of mulching plastic film and controlling measures[J]. Transactions of the CSAE, 2006, 22(11): 269-272

[4] Yan C R, Liu E K, Shu F, et al. Review of agricultural plastic mulching and its residual pollution and prevention measures in China[J]. Journal of Agricultural Resources and Environment, 2014, 31(2): 95-102

[5] Zhang D, Hu W L, Liu H B, et al. Characteristics of residual mulching film and residual coefficient of typical crops in North China[J]. Transactions of the CSAE, 2016, 32(3): 1-5

[6] Ma H, Mei X R, Yan C R, et al. The residue of mulching plastic film of cotton field in North China[J]. Journal of Agro-Environment Science, 2008, 27(2): 570-573

[7] Li X Y, Shi H B, Lü Y, et al. Effects of different residual plastic film quantities in soil on drip infiltration and its uncertainty analysis[J]. Transactions of the CSAE, 2013, 29(8): 84-90

[8] Wang Z C, Li X Y, Shi H B, et al. Study on effect of plastic film residue at different buried depths on silt loam drip infiltration[J]. Soils, 2014, 46(4): 710-715

[9] Wang Z C, Li X Y, Shi H B, et al. Effects of residual plastic film on soil hydrodynamic parameters and soil structure[J]. Transactions of the CSAM, 2015, 46(5): 101-106

[10] Li Y Q, He W Q, Yan C R, et al. Effect of residual film on soil infiltration under drip irrigation[J]. Transactions of the CSAE, 2015, 31(6): 145-149

[11] Liu J G, Li Y B, Zhang W, et al. The distributing of the residue film and influence on cotton growth under continuous cropping in oasis of Xinjiang[J]. Journal of Agro-Environment Science, 2010, 29(2): 246-250

[12] Xie H E, Li Y S, Yang S Q, et al. Influence of residual plastic film on soil structure, crop growth and development in fields[J]. Journal of Agro-Environment Science, 2007, 26(S1): 291-293

[13] Dong H G, Liu T, Li Y G, et al. Effects of plastic film residue on cotton yield and soil physical and chemical properties in Xinjiang[J]. Transactions of the CSAE, 2013, 29(8): 91-99

[14] Gao Y S, Sun Y Y, Dou J G, et al. Effects of plastic film residue on emergence and root growth of corn seedlings[J]. Journal of Jilin Agricultural Sciences, 2013, 38(6): 22-24

[15] Xin J J, Shi H B, Li X Y, et al. Effects of plastic film residue on growth and yield of maize[J]. Journal of Irrigation and Drainage, 2014, 33(3): 52-54

[16] Han F X, Chang L, Chai S X, et al. Effect of straw strip covering on ridges on soil water content and potato yield under rain-fed semiarid conditions[J]. Chinese Journal of Eco-Agriculture, 2016, 24(7): 874-882

[17] Cui N B, Du T S, Li Z T, et al. Effects of regulated deficit irrigation at different growth stages on greenhouse pear-jujube quality[J]. Transactions of the CSAE, 2009, 25(7): 32-38

[18] Dong H G, Wang D, Wang Y T, et al. Spatial and temporal distribution characteristics of mulch residues in cotton field in Shihezi, Xinjiang[J]. Journal of Arid Land Resources and Environment, 2013, 27(9): 182-186

[19] Qian Y Q, Sun Z Y, Han L, et al. Simulation of clonal growth curve based on nonlinear models of Logistic and Gompertz for buffalograss [*Buchloe dactyloides* (Nutt.) Engelm Texoka][J]. Scientia Agricultura Sinica, 2011, 44(11): 2252-2259

[20] Wang H, Bai Y L, Yang L P, et al. A summer maize dressing decision-making model based on effective accumulated temperature[J]. Chinese Journal of Eco-Agriculture, 2012, 20(4): 408-413

[21] Zhao Y L, Xue Z W, Guo H B, et al. Effects of tillage and residue management on soil respiration and mechanism[J]. Transactions of the CSAE, 2014,

30(19): 155-165

[22] Nosalewicz A, Lipiec J. The effect of compacted soil layers on vertical root distribution and water uptake by wheat[J]. Plant and Soil, 2014, 375(1/2): 229-240

[23] Gupta B, Shah D O, Mishra B, et al. Effect of top soil wettability on water evaporation and plant growth[J]. Journal of Colloid and Interface Science, 2015, 449: 506-513

[24] Zhang J, Liu J, Chen H, et al. Change in soil oxygen and water contents under alternate wetting and drying in paddy fields[J]. Chinese Journal of Eco-Agriculture, 2014, 22(4): 385-391

[25] Cook F J, Orchard V A. Relationships between soil respiration and soil moisture[J]. Soil Biology and Biochemistry, 2008, 40(5): 1013-1018

[26] Kuster T M, Arend M, Günthardt-Goerg M S, et al. Root growth of different oak provenances in two soils under drought stress and air warming conditions[J]. Plant and Soil, 2013, 369(1/2): 61-71

[27] Wang J, Li X G, Liu E M, et al. The relationship between relative evapotranspiration and leaf area index and surface soil water content in winter wheat field of North China Plain[J]. Chinese Journal of Eco-Agriculture, 2003, 11(2): 32-34

[28] Xue L H, Duan J J, Wang Z M, et al. Effects of different irrigation regimes on spatial-temporal distribution of roots, soil water use and yield in winter wheat[J]. Acta Ecologica Sinica, 2010, 30(19): 5296-5305

[29] Ding H, Zhang Z M, Dai L X, et al. Effects of drought stress on root growth characteristics of peanut during mid-to-late growth stages[J]. Chinese Journal of Eco-Agriculture, 2013, 21(12): 1477-1483

[30] Ma X F, Yu T, Wang L H, et al. Effects of water deficit at seedling stage on maize root development and anatomical structure[J]. Chinese Journal of Applied Ecology, 2010, 21(7): 1735-1741

[31] Yang T, Xie Z X, Yu Q, et al. Effects of partial root salt stress on seedling growth and photosynthetic characteristics of winter wheat[J]. Chinese Journal of Eco-Agriculture, 2014, 22(9): 1074-1078

[32] Liu W G, Shan L. Effect of soil mechanical resistance on hydraulic conductivity of maize root[J]. Journal of Hydraulic Engineering, 2004, 35(4): 114-117

[33] Han G J, Chen N L, Li J X, et al. Response of stomatal conductance and osmotic adjustment substances accumulation to rapid drought stress in tomato leaves[J]. Chinese Journal of Eco-Agriculture, 2013, 21(9): 1100-1106

[34] Sun H Y, Zhang X Y, Chen S Y, et al. Effects of deficit irrigation on physio-ecological indices of winter wheat[J]. Chinese Journal of Eco-Agriculture, 2011,

19(5): 1086-1090

[35] Wang L L, Chen W, Xu Y, et al. Nitrogen nutrition affects dry matter accumulation and transportation in winter wheat[J]. Acta Agriculturae Boreli-occidentalis Sinica, 2013, 22(10): 85-89

[36] Flexas J, Bota J, Galmés J, et al. Keeping a positive carbon balance under adverse conditions: Responses of photosynthesis and respiration to water stress[J]. Physiologia Plantarum, 2006, 127(3): 343-352

[37] Tan N T, Lin Q, Jiang W, et al. Effect of limited irrigation on diurnal variation in flag-leaf photosynthesis and yield of dryland wheat[J]. Chinese Journal of Eco-Agriculture, 2011, 19(4): 805-811

[38] Acevedo E, Hsiao T C, Henderson D W. Immediate and subsequent growth responses of maize leaves to changes in water status[J]. Plant Physiology, 1971, 48(5): 631-636

[39] Wang L B, Zu W, Dong S K, et al. Effects of drought stresses and times on compensation effect after re-watering soybean[J]. Transactions of the CSAE, 2015, 31(11): 150-156

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.