Effect of Plastic Film Residue on Vertical Infiltration Under Different Initial Soil Moisture Contents and Dry Bulk Densities

Junhao Cao, Pengpeng Chen, Yupeng Li, Heng Fang, Xiaobo Gu * and Yuannong Li *

Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semi-arid Areas, Ministry of Education, Northwest A&F University, Yangling 712100, Shanxi, China; xinongcaojunhao@163.com (J.C.); 15129248421@163.com (P.C.); yupeng_li@nwafu.edu.cn (Y.L.); fangheng8571@163.com (H.F.)

* Correspondence: guxiaobo@nwafu.edu.cn (X.G.); liyuannong@163.com (Y.L.)

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Abstract: In arid and semi-arid regions, plastic film mulching can effectively improve crop yield, but with the increase of service life, a lot of residual plastic film (RPF) remains in the soil. The application of a RPF to a soil will alter soil moisture processes, and thus, affect the soil water distribution and its effectiveness. A quadratic regression orthogonal design was used to study the effects of initial moisture content (IMC), dry bulk density (DBD), residual plastic film content (RPFC), and the burial depth of RPF on the migration time of wetting front (MF), moisture content (MC), and accumulative infiltration (AI) of a test soil. It was found that IMC, DBD, and RPFC were the main factors affecting MC, MF, and AI, while the burial depth of RPF had no significant influence. The order of influence for the factors affecting MF was IMC > DBD > RPFC, while the order of influence for the factors affecting MC and AI was DBD > IMC > RPFC. RPFC was parabolic in relation to MF, MC, and AI, when it was in the range of 50–100 kg/hm², while within the same range MC and AI reached a maximum and MF reached a minimum. The analysis of the interactive responses revealed that when the DBD was greater than 1.29 g/cm³, the MF initially decreased and then increased with the increase of RPFC. When the RPFC was more than 100 kg/hm², the MF initially increased and then decreased with the increase of DBD. When the DBD was larger than 1.31 g/cm³, the AI initially increased and then decreased with the increase of RPFC. It was apparent that the RPF not only had a blocking effect on the wetting front, but also affected the water flow. When the RPFC was between 50 and 100 kg/hm², the soil MC was significantly increased. It was suggested that the RPF pollution area should increase the mechanical recovery of plastic film, standardize the use and recycling of agricultural RPF, optimize the planting model, and establish a recyclable model for the treatment of RPF pollution, and it was proposed that the RPFC remaining after recovery of the RPF should be less than 50 kg/hm². This study can prove the law of soil water movement in the residue film pollution area and provide reference and solution ideas for the comprehensive treatment of residue film pollution in farmland.

Keywords: residual plastic film; burial depth; moisture content; wetting front of migration time; accumulative infiltration

1. Introduction

Since the 1950s, plastic film mulching technology has been widely used agricultural production processes worldwide [1,2]. At present, there are two main methods of plastic film mulching: Surface mulching and ridge-furrow mulching [3,4]. According to the research, plastic film mulching technology can reduce soil evaporation [5,6], improve crop yield and quality [7,8], improve the surface water use efficiency in water shortage areas [9], and it can also increase the surface temperature to promote crop emergence [10]. In arid and semi-arid areas, most farmers have been
using plastic film mulching technology to increase crop yield in order to increase their income [11]. Plastic film plays an important role in agriculture in arid and semi-arid areas [12].

However, with the long-term use of this technology, the accumulation of residual plastic in the soil during mulching applications has been ignored [13]. In 2014, the global use of plastic film was 1.4 million tons [14]. The agricultural use of plastic film is continuing to increase [15]. The physical and chemical properties of the cultivated soil and its nutritional status can be significantly decreased [16], seriously hindering the development of the crop root system [17,18] and its absorption and utilization of water and fertilizer [19,20]. The accumulation of residual plastic has resulted in a continuous decline of the land production capacity in areas affected by the long-term use of plastic film [19,21], restricting the sustainable development of agricultural ecosystems, causing water bodies pollution [22], and leading to the “white revolution” of mulch being referred to as “white pollution” or even a “white disaster” [23,24]. Due to a lack of environmental awareness, the problem of residual plastic film (RPF) affecting soil productivity has been ignored for a long time [13,25]. In addition, to reduce production costs, the thickness of the plastic film applied has decreased in recent years, which has led to an increased incidence of film breakage, while recovery has become more difficult. The accumulation rate of RPF in agricultural soils is accelerating, and the area of polluted land is expanding [26]. In the long term, the negative outcomes of plastic film pollution will gradually outweigh the economic benefits of the heat and moisture preservation [27,28]. However, the large production costs of degradable membranes make them difficult to promote [29]. Therefore, plastic film cannot currently be replaced by alternative products.

In recent years, membrane fouling as a form of “white pollution” has been taken seriously by agricultural, water conservancy, and environmental professionals [24,30,31], with most plastic film mulch research focusing on the film thickness [32], material [15], the potential for biodegradable films [13], and covering effects [33,34]. There has been less focus on the impact of RPF on soil infiltration and soil water redistribution, with problems such as soil moisture availability receiving little attention. Previous studies have been conducted to investigate the influence of RPF and burial depth of RPF on soil infiltration [35]. The influence of excessive applications and burial depths of RPF have been considered as single factors [36] and the relationship between the soil Mc and the migration time of wetting front (Mt) and the burial depth of RPF, RPFc, dry bulk density (Db), and initial moisture content (Imc) need to be studied in terms of their interactive effects on the Mt and their influence on soil Mc.

Therefore, this study used a quadratic regression orthogonal experimental design to: (1) Determine the influence of RPFc, burial depth of RPF, Db, and Imc on the Mt and soil Mc; (2) determine the influence of the interactions between two factors on the Mt and soil Mc; (3) establish an optimal RPFc and soil permeability, where the relationship between the plastic film and land use does not influence the production capacity of the land; and (4) determine a theoretically reasonable irrigation system in areas affected by plastic membrane pollution.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted at an experimental station (34°18′N, 108°24′E; 521 m a.s.l.) of the Key Laboratory of Agricultural Soil and Water Engineering, Ministry of Education, Northwest A & F University, located in Yangling, Shaanxi Province in northwest China. The experimental site was flat and open terrain, with abundant light and heat resources. The average sunshine per year of 2527.1h, average annual temperature of 13 °C (obtained at Yangling Meteorological Bureau). The average evaporation was 1500 mm and the groundwater depth was 80 m, with the area being classed as semi-humid and drought-prone.

2.2. Experimental Materials and Devices

Soil samples were taken from the surface of the test field in the experimental station. The texture of the soil was a loam. After removing impurities such as plant roots and stones, air drying,
mechanical rolling, and passing through a 5mm screen the IMC was 2.0%. Soil particle size was
determined by an MS2000 laser particle size analyzer (Malvern Instruments, Malvern, UK). Clay
particles (d < 0.002mm) comprised 22.1% of the soil, fine particles (0.002 < d < 0.005mm) accounted
for 5.8%, medium sized powder (0.005 < d < 0.02mm) accounted for 26.4%, powder (0.02 < d < 0.05
mm) accounted for 37.8%, and extremely fine sand (0.05 < d < 0.25 mm) accounted for 7.93%. The
saturated hydraulic conductivity and saturated soil moisture were 24.36 cm d\(^{-1}\) and 0.48 cm\(^3\) cm\(^{-3}\),
respectively. The soil organic carbon was 6.50 g kg\(^{-1}\). The dry bulk density of soil was 1.40 g cm\(^{-3}\). The
basic physical and chemical shape of soil was: organic matter 11.20 g kg\(^{-1}\), total nitrogen 0.93 g kg\(^{-1}\),
nitrate nitrogen 76.27 mg kg\(^{-1}\), available phosphorus 25.38 mg kg\(^{-1}\), available potassium 131.97 mg
kg\(^{-1}\), PH value was 8.12.

The transparent film thickness was 0.008mm (Shandong Xifeng Plastic Industry Co., Ltd.,
Shandong, China). The centrifuge method is used to obtain soil hydraulic parameters for the soil
moisture characteristic curve [37]. Determination of soil moisture characteristic curve (Figure 1) by
CR21GII high speed constant temperature freezing centrifuge made in Japan.

![Figure 1. Soil moisture characteristic curve.](image)

As shown in Figure 2, the test device had a Mariotte’s bottle height of 70 cm, the soil column
height was 60 cm, and radius (r) = 12 cm. The Mariotte’s bottle and soil column were made of
plexiglass. There was a water outlet at the bottom of the Mariotte’s bottle at 2 cm, and a 67 cm long
plexiglass pipe was placed inside. The lower end of the plexiglass tube was 6 cm higher than the soil
surface in the soil column (the infiltration head was maintained constantly at 6 cm). There was an air
vent at the lower end of the soil column, located 2 cm from the base. During the infiltration process,
the air in the soil was discharged through the air vent to maintain the pressure balance in the
infiltration process. The bottom 5 cm of the soil column was filled with quartz stone, and 5 cm of
settled soil was laid on the quartz stone (to prevent the test soil sample from entering the quartz stone
crack). The soil in the column was divided into four sections (0–10, 10–20, 20–30, and 30–40 cm soil
layers). Two round holes (r = 1 cm) were made in the middle part of each layer to enable the
measurement of soil MC at the end of the test, and rubber plugs were used to seal the holes and
prevent leakage during the experiment.
2.3. Design and Methods

2.3.1. Experimental Design

Four factors (IMC, DBD, RPFC, and burial depth of RPF) were selected for testing in the experiment, with each factor selected at five levels. A four-factor and five-level quadratic regression orthogonal experimental design was adopted. Each factor had five levels and a total of 36 combinations. Each combination was repeated three times and the results were averaged. The horizontal coding tables of each factor are shown in Table 1 and the experimental scheme is shown in supplementary materials.

Table 1. Test factors and levels.

| Zj | IMC   | DBD  | RPFC  | Burial Depth of RPF/cm |
|----|-------|------|-------|------------------------|
|    | Z1(%) | Z2/(g/cm³) | Z3/(kg/hm²) |                       |
| r (2) | 16 | 1.45 | 200  | 30–40                   |
| 1     | 14 | 1.41 | 150  | 20–30                   |
| 0     | 11 | 1.35 | 100  | 10–20                   |
| −1    | 8  | 1.29 | 50   | 0–10                    |
| r (−2)| 6  | 1.25 | 0    | 0                       |

IMC, DBD, RPFC and RPF represents mean initial moisture content, dry bulk density, residual plastic film content and residual plastic film, respectively.

2.3.2. Data Analysis

When there are p variables, the general form of a quadratic regression equation is:

\[
y = b_0 + \sum_{j=1}^{p} b_j x_j + \sum_{k=1}^{p-1} \sum_{j=k+1}^{p} b_{kj} x_k x_j + \sum_{j=1}^{p} b_j x_j^2
\]  

(1)

(1) Calculation of bj

\[
b_0 = \frac{B_0}{n}, \quad b_j = \frac{B_j}{d_j}, \quad b_{kj} = \frac{B_{kj}}{d_{kj}}, \quad b_{jj} = \frac{B_{jj}}{d_{jj}}
\]  

(2)

Where n denotes the number of tests,
\[ d_j = \sum_{i=1}^{n} z_{ij}^2, \quad d_{kj} = \sum_{i=1}^{n} (z_{ik}z_{ij})^2, \quad d_{jj} = \sum_{i=1}^{n} (z_{ij})^2 \]  

(3) Calculation of \( B_j \):

\[
B_0 = \sum_{i=1}^{n} y_i, \quad B_j = \sum_{i=1}^{n} z_{ij}y_i, \quad B_{kj} = \sum_{i=1}^{n} z_{ik}z_{ij}y_i, \quad B_{jj} = \sum_{i=1}^{n} z_{ij}y_i
\]  

(4) where \( Z_k \) represents the data corresponding to row \( i \) of \( Z \) in supplementary materials, \( Z' \) represents the data corresponding to row \( i \) of \( Z' \) in supplementary materials, and \( y \) represents the data corresponding to row \( i \) of \( y \) in supplementary materials.

2.3.2.1. Testing of the Regression Equation

\[
F = \frac{U/f_u}{Q_{e2}/f_{e2}} \sim F(f_u, f_{e2})
\]  

(5) The remaining sum of squares is:

\[
Q_{e2} = \sum_{i=1}^{n} y_i^2 - b_0B_0 - \sum_{j=1}^{p} b_jB_j - \sum_{k=1}^{p} \sum_{j=k+1}^{p} b_{kj}B_{kj} - \sum_{j=1}^{p} b_{jj}B_{jj}, \quad f_{e2} = n - C_{p+2}^2
\]  

(6) (2) Regression square sum:

\[
U = SS_T - Q_{e2}, \quad f_u = C_{p+2}^2 - 1
\]  

(7) (3) Total sum of squares:

\[
SS_T = \sum_{i=1}^{n} y_i^2 - \frac{1}{n} \left( \sum_{i=1}^{n} y_i \right)^2
\]  

(8)

2.3.2.2. Testing of the Fitting Degree of the Equation:

\[
F_{LF} = \frac{Q_{LF}/f_{LF}}{Q_{e}/f_e} \sim F(f_u, f_{e2})
\]  

(9) (1) The sum of squares of errors is obtained from the zero level test results:

\[
Q_e = \sum_{i=n-f_e}^{n} y_i^2 - \frac{1}{m_0} \left( \sum_{i=n-f_e}^{n} y_i^2 \right)^2, \quad f_e = m_0 - 1
\]  

(10) where, \( m_0 \) is the number of zero level tests.

(2) Loss of quasi-sum of squares:

\[
Q_{LF} = Q_{e2} - Q_e, f_{LF} = f_{e2} - f_e
\]  

(11)

All data were obtained from the average of three repeated trials. The regression equation and the fitting degree of the equation were tested using the above formulas (Equation (1) (5) (9)). Origin 8.0 was used to analyze the single factor effect, and Matlab was used to analyze the effect of interaction between the two factors.

3. Results

3.1. Analysis of the Mr
The wetting front refers to the obvious interface between the wetted part of the soil and the dry soil layer during the process of water infiltration, and it therefore indicates the state of water movement [38]. The distribution of soil water indirectly reflected the blocking effect of RPF on water movement. The Rw in the field blocks the soil pores and restricts soil water movement, which results in a decrease in the soil water carrying capacity and affects the movement and distribution of the moisture front.

Based on the experimental results and calculations, quadratic regression models of MF and IMC, DBD, RPFC, and burial depth of RPF were obtained. An analysis of variance (ANOVA) of the quadratic regression models was conducted. The results are shown in Table 2. The results showed that the linear terms of IMC, RPFC, and DBD, the quadratic terms of RPFC and DBD, and the interaction terms of IMC and DBD, DBD and RPFC reached significant levels (P < 0.01), while the other terms were not significant. A simplified regression equation (Equation (12) was obtained after eliminating the non-significant items. Because an orthogonal design was adopted and all factors were coded by non-coding, all regression coefficients were independent of each other. Therefore, the remaining factors were fixed at zero, and an equation describing the relationship between the single factor and the MF was obtained. A diagram showing the relationship between the single factor and the MF was constructed using Origin. The same procedure was used to determine the relationship between the two-factor interaction effect and the MF, and a three-dimensional figure was constructed using Matlab.

Table 2. The MF statistical analysis and analysis of variance results.

| Variance Source | Sum of Squares | Degree of Freedom | Mean Square | Partial Correlation | F-Ratio | P  |
|-----------------|----------------|------------------|-------------|---------------------|---------|----|
| Z1              | 430,408.2      | 1                | 430,408.2   | -0.9648             | 282.3304| 0.0001|
| Z2              | 175,788.2      | 1                | 175,788.2   | 0.9197              | 115.3099| 0.0001|
| Z3              | 58,608.17      | 1                | 58,608.17   | 0.8042              | 38.4446 | 0.0001|
| Z4              | 80.6667        | 1                | 80.6667     | -0.0501             | 0.0529  | 0.8203|
| Z1^2            | 62.3472        | 1                | 62.3472     | 0.0441              | 0.0409  | 0.8417|
| Z2^2            | 14,252.35      | 1                | 14,252.35   | -0.555              | 9.349   | 0.006 |
| Z3^2            | 20,234.01      | 1                | 20,234.01   | 0.6223              | 13.2727 | 0.0015|
| Z1Z2            | 28,392.25      | 1                | 28,392.25   | -0.6856             | 18.6242 | 0.0003|
| Z1Z3            | 12.25          | 1                | 12.25       | 0.0196              | 0.008   | 0.9294|
| Z1Z4            | 72.25          | 1                | 72.25       | 0.0475              | 0.0474  | 0.8298|
| Z2Z3            | 37,442.25      | 1                | 37,442.25   | -0.7342             | 24.5606 | 0.0001|
| Z2Z4            | 2652.25        | 1                | 2652.25     | 0.2766              | 1.7398  | 0.2014|
| Z3Z4            | 702.25         | 1                | 702.25      | -0.1465             | 0.4606  | 0.5047|
| Regression      | 774,098.1      | 14               | 55,292.72   |                     | F2=36.26979 | 0.0001|
| Residual        | 32,014.17      | 21               | 1524.48     |                     |         |      |
| Lack of fit     | 22,307.92      | 10               | 2230.792    |                     | F1=2.52813 | 0.0001|
| Error           | 9706.25        | 11               | 882.3864    |                     |         |      |
| Sum             | 806,112.2      | 35               |             |                     |         |      |

From Equation (12), it can be seen that the factors affecting MF followed the order of IMC > DBD > RPFC (133.92 > 85.58 > 49.42). It can be seen from Figure 3 that the MF decreased linearly with the increase of IMC and the MF increased with the increase of DBD, but the growth rate decreased slowly. The MF initially decreased and then increased with the increase of RPFC, reaching a minimum when the RPFC was 51 kg/hm² (Z3 = -0.98). It can be seen from Figure 4 that when the DBD was greater than 1.29 g/cm³ (Z2 > -1), the MF initially decreased and then increased with the increase of RPFC. When the DBD of soil was less than 1.29 g/cm³ (Z2 < -1), the MF increased with the increase of RPFC. When the RPFC was more than 100 kg/hm² (Z3 > 0), the MF initially decreased and then increased with the increase of the DBD. When the RPFC was less than 100 kg/hm² (Z3 < 0), the MF increased with the increase of DBD.
Figure 3. The relationships among Mf and various factors. Z1, Z2, and Z3 represents mean initial moisture content, dry bulk density and residual plastic film content, respectively.

Figure 4. Surface interaction effects between DBD and RPFC. Z2 and Z3 represents mean dry bulk density and residual plastic film content respectively.

3.2. Analysis of the Accumulative Infiltration (AI)

Accumulative infiltration refers to the total amount of water infiltrated into the soil through the surface per unit area in a certain period of time after the beginning of infiltration [39]. It can indirectly reflect the degree of blocking of soil water movement by RPFC. The distribution of soil water indirectly reflected the blocking effect of RPFC on water movement. The RPFC in the field blocks the soil pores, limiting soil water movement. This results in a decrease in the soil water carrying capacity and affects the movement and distribution of the moisture front. According to the analysis method described in data analysis, regression equations were obtained for AI and IMC, DBD, RPFC, and burial depth of RPFC, and an ANOVA of the regression equation was conducted, with the results shown in Table 3. After eliminating the non-significant items, the simplified regression equation shown in Equation (13) was obtained.

\[
Y = 441.25 - 133.92Z_1 + 85.58Z_2 + 21.10Z_2^2 + 25.15Z_3^2 - 42.13Z_1Z_2 - 48.38Z_2Z_3
\]  (12)
Table 3. The AI statistical analysis and analysis of variance results.

| Factors | Sum of Squares | Degree of Freedom | Mean Square | Partial Correlation | F-Ratio | P     |
|---------|----------------|-------------------|-------------|---------------------|---------|-------|
| Z₁      | 1,985,291      | 1                 | 1,985,291   | −0.7791             | 32.4444 | 0.0001|
| Z₂      | 13,841,432     | 1                 | 13,841,432  | −0.9566             | 226.2023 | 0.0001|
| Z₃      | 1,303,728      | 1                 | 1,303,728   | −0.7097             | 21.3061 | 0.0001|
| Z₄      | 9680.97        | 1                 | 9680.97     | −0.0865             | 0.1582  | 0.6948|
| Z₁²     | 129,160.7      | 1                 | 129,160.7   | −0.3022             | 2.1108  | 0.161 |
| Z₂²     | 484,006.6      | 1                 | 484,006.6   | 0.5231              | 7.9098  | 0.0104|
| Z₃²     | 503,850.7      | 1                 | 503,850.7   | −0.5307             | 8.2341  | 0.0092|
| Z₄²     | 87,288.17      | 1                 | 87,288.17   | −0.2522             | 1.4265  | 0.2457|
| Z₁Z₂    | 58,888.73      | 1                 | 58,888.73   | −0.2093             | 0.9624  | 0.3378|
| Z₁Z₃    | 104,022.4      | 1                 | 104,022.4   | 0.2737              | 1.7     | 0.2064|
| Z₁Z₄    | 26,511.98      | 1                 | 26,511.98   | 0.1422              | 0.4333  | 0.5175|
| Z₂Z₃    | 2,447,723      | 1                 | 2,447,723   | 0.8098              | 40.0017 | 0.0001|
| Z₂Z₄    | 20,067.56      | 1                 | 20,067.56   | 0.124               | 0.328   | 0.5729|
| Z₃Z₄    | 14,174.09      | 1                 | 14,174.09   | 0.1045              | 0.2316  | 0.6353|
| Regression | 21,015,826     | 14                | 1,501,130   | F² = 24.53208       | 0.0001  |       |
| Residual | 1,285,001      | 21                | 61,190.51   |                     |         |       |
| Lack of fit | 1,244,848    | 10                | 124,484.8   | F¹ = 34.10330       | 0.0001  |       |
| Error   | 40,152.51      | 11                | 3650.228    |                     |         |       |
| Sum     | 22,300,827     | 35                |             |                     |         |       |

By comparing the absolute values of the coefficients for each factor, the influence of each factor on the AI was determined and was found to follow the order of DBD > IMC > RPFC (759.43 > 287.61 > 233.07). The other factors were fixed to zero to obtain an equation describing the relationship between each single factor and AI, and a diagram to highlight this was constructed with Origin (Figure 5). From Figure 5, it can be seen that the AI decreased linearly with the increase of IMC and DBD, with the relationship having a negative correlation. The AI initially increased and then decreased with the increase of RPFC, displaying a parabolic curve. When the RPFC reached 53kg/hm² (Z₃ = −0.94), the AI reached its maximum value. By fixing the IMC at zero, an equation describing the relationship of AI, DBD, and RPFC was obtained and Matlab was used to construct a three-dimensional diagram (Figure 6). The analysis of the interaction effect showed that when the DBD was more than 1.31 g/cm³ (Z₂ = −0.69), the AI initially increased and then decreased with the increase of RPFC. When the DBD was less than 1.31 g/cm³ (Z₂ = −0.69), the AI decreased linearly with the increase of RPFC.

\[ Y = 5552.55 - 287.61Z₁ - 759.43Z₂ - 233.07Z₃ - 125.48Z₂² + 391.13Z₂Z₃ \]
Figure 5. The relationships among $A_i$ and various factors. $Z_1$, $Z_2$, and $Z_3$ represents mean initial moisture content, dry bulk density, and residual plastic film content, respectively.

Figure 6. Surface interaction effects between $D_{BD}$ and $R_{PFC}$. $Z_2$ and $Z_3$ represents mean dry bulk density and residual plastic film content respectively.

3.3. Analysis of the $MC$

Soil $MC$ refers to the ratio of the weight of water in the soil to the weight of the corresponding solid phase material [40]. According to the analysis method used in data analysis, regression equations were obtained for $MC$ and $IMC$, $D_{BD}$, $R_{PFC}$, and burial depth of $R_{PF}$, and an ANOVA of the regression equation was conducted, with the results shown in Tables 4–7. According to these tables, regression equations between $MC$ in each layer and each factor were obtained after eliminating the insignificant items (Equations (14–17)). These four equations were used to describe the relationship between the $MC$ in each layer and each factor (Figure 7). It can be seen from the figure that the $MC$ in the four layers declined linearly with the increase in $IMC$ and $D_{BD}$, with the relationships having a negative correlation. With the increase of $R_{PFC}$, the $MC$ initially increased and then decreased. In the 0–10cm layer, when the $R_{PFC}$ was 74kg/hm$^2$ ($Z_3 = -0.52$), the $MC$ reached a maximum. In the layer 10–20cm, when the $R_{PFC}$ was 68kg/hm$^2$ ($Z_3 = -0.64$), the $MC$ reached a maximum. In the 20–30cm layer, when the $R_{PFC}$ was 71kg/hm$^2$ ($Z_3 = -0.58$), the $MC$ reached a maximum. In the 30–40cm layer, when the $R_{PFC}$ was 59kg/hm$^2$ ($Z_3 = -0.82$), the $MC$ reached a maximum. There was no significant effect of burial depth of $R_{PF}$ on soil $MC$, and there was no interaction between the two factors.

\[
Y(0–10cm) = 31.87 - 1.30Z_1 - 1.81Z_2 - 0.46Z_3 - 0.44Z_3^2
\]  \hfill (14)

\[
Y(10–20cm) = 31.09 - 1.32Z_1 - 2.06Z_2 - 0.56Z_3 - 0.44Z_3^2
\]  \hfill (15)

\[
Y(20–30cm) = 29.77 - 1.02Z_1 - 2.04Z_2 - 0.58Z_3 - 0.50Z_3^2
\]  \hfill (16)

\[
Y(30–40cm) = 26.09 - 1.02Z_1 - 1.67Z_2 - 0.61Z_3 - 0.37Z_3^2
\]  \hfill (17)
Figure 7. The relationships among MC and various factors. \(Z_1\), \(Z_2\), and \(Z_3\) represents mean initial moisture content, dry bulk density, and residual plastic film content, respectively.

Table 4. The 0–10 cm MC statistical analysis and analysis of variance results.

| Factors | Sum of Squares | Degree of Freedom | Mean Square | Partial Correlation | F-Ratio | P     |
|---------|---------------|-------------------|-------------|---------------------|---------|-------|
| \(Z_1\) | 40.3782       | 1                  | 40.3782     | -0.89               | 79.9942 | 0.0001|
| \(Z_2\) | 78.9525       | 1                  | 78.9525     | -0.939              | 156.4148| 0.0001|
| \(Z_3\) | 5.0508        | 1                  | 5.0508      | -0.5681             | 10.0063 | 0.0047|
| \(Z_4\) | 0.0002        | 1                  | 0.0002      | -0.0044             | 0.0004  | 0.9841|
| \(Z_2^2\) | 0.0458       | 1                  | 0.0458      | -0.0656             | 0.0906  | 0.7663|
| \(Z_3^2\) | 3.8157        | 1                  | 3.8157      | 0.5145              | 7.5594  | 0.012 |
| \(Z_3^2\) | 6.1864        | 1                  | 6.1864      | -0.6071             | 12.256  | 0.0021|
| \(Z_4^2\) | 2.2103        | 1                  | 2.2103      | 0.4154              | 4.3788  | 0.0487|
| \(Z_2Z_3\) | 0.8236        | 1                  | 0.8236      | 0.2685              | 1.6316  | 0.2154|
| \(Z_2Z_3\) | 0.6765        | 1                  | 0.6765      | -0.2449             | 1.3402  | 0.26  |
| \(Z_2Z_4\) | 2.4571        | 1                  | 2.4571      | -0.4338             | 4.8677  | 0.0386|
| \(Z_3Z_4\) | 1.8701        | 1                  | 1.8701      | 0.3873              | 3.7048  | 0.0679|
| \(Z_3Z_4\) | 0.2377        | 1                  | 0.2377      | -0.1481             | 0.4708  | 0.5001|
| \(Z_3Z_4\) | 1.2939        | 1                  | 1.2939      | -0.3298             | 2.5634  | 0.1243|

Regression: 143.9986, 14, 10.2856, F2 = 20.37708, 0.0001
Residual: 10.6, 21, 0.5048
Lack of fit: 10.3697, 10, 1.037, F1 = 49.52981, 0.0001
Error: 0.2303, 11, 0.0209
Sum: 154.5987, 35
### Table 5. The 10–20 cm MC statistical analysis and analysis of variance results.

| Factors | Sum of Squares | Degree of Freedom | Mean Square | Partial Correlation | F-Ratio | P     |
|---------|----------------|-------------------|-------------|---------------------|---------|-------|
| Z1      | 41.554         | 1                 | 41.554      | −0.851              | 55.158  | 0.0001|
| Z2      | 102.0113       | 1                 | 102.0113    | −0.930              | 135.4094| 0.0001|
| Z3      | 7.5264         | 1                 | 7.5264      | −0.5678             | 9.9905  | 0.0047|
| Z4      | 0.1442         | 1                 | 0.1442      | −0.095              | 0.1913  | 0.6663|
| Z1^2    | 1.4706         | 1                 | 1.4706      | 0.2916              | 1.9521  | 0.177 |
| Z2^2    | 0.5778         | 1                 | 0.5778      | 0.1877              | 0.767   | 0.391 |
| Z3^2    | 6.2481         | 1                 | 6.2481      | −0.5321             | 8.2937  | 0.009 |
| Z4^2    | 0.3828         | 1                 | 0.3828      | 0.1537              | 0.5081  | 0.4838|
| Z1Z2    | 0.6241         | 1                 | 0.6241      | 0.1948              | 0.8284  | 0.3731|
| Z1Z3    | 1.092          | 1                 | 1.092       | −0.2541             | 1.4496  | 0.242 |
| Z1Z4    | 1.199          | 1                 | 1.199       | −0.2654             | 1.5916  | 0.2209|
| Z2Z3    | 1.3924         | 1                 | 1.3924      | 0.2844              | 1.8483  | 0.1884|
| Z2Z4    | 0.0625         | 1                 | 0.0625      | −0.0627             | 0.083   | 0.7761|
| Z3Z4    | 0.7656         | 1                 | 0.7656      | −0.2149             | 1.0163  | 0.3249|

Regression: 165.0509 14 11.7893 F = 15.64914 0.0001

Residual: 15.8204 21 0.7534

Lack of fit: 14.5316 10 1.4532 F1 = 12.40190 0.0001

Error: 1.2889 11 0.1172

Sum: 180.8713 35

### Table 6. The 20–30 cm MC statistical analysis and analysis of variance results.

| Factors | Sum of Squares | Degree of Freedom | Mean Square | Partial Correlation | F-Ratio | P     |
|---------|----------------|-------------------|-------------|---------------------|---------|-------|
| Z1      | 24.8067        | 1                 | 24.8067     | −0.7409             | 25.5609 | 0.0001|
| Z2      | 99.5523        | 1                 | 99.5523     | −0.9111             | 102.5792| 0.0001|
| Z3      | 7.958          | 1                 | 7.958       | −0.5299             | 8.2     | 0.0093|
| Z4      | 0.028          | 1                 | 0.028       | −0.0371             | 0.0289  | 0.8667|
| Z1^2    | 0.091          | 1                 | 0.091       | 0.0667              | 0.0938  | 0.7624|
| Z2^2    | 0.9614         | 1                 | 0.9614      | 0.2122              | 0.9907  | 0.3309|
| Z3^2    | 7.854          | 1                 | 7.854       | −0.5274             | 8.028   | 0.0097|
| Z4^2    | 0.2568         | 1                 | 0.2568      | 0.1116              | 0.2646  | 0.6123|
| Z1Z2    | 0.6006         | 1                 | 0.6006      | 0.1692              | 0.6189  | 0.4402|
| Z1Z3    | 0.0042         | 1                 | 0.0042      | 0.0144              | 0.0044  | 0.948 |
| Z1Z4    | 0.5256         | 1                 | 0.5256      | −0.1586             | 0.5416  | 0.4699|
| Z2Z3    | 1.113          | 1                 | 1.113       | 0.2276              | 1.1469  | 0.2964|
| Z2Z4    | 3.441          | 1                 | 3.441       | −0.3801             | 3.5457  | 0.0736|
| Z3Z4    | 0.3906         | 1                 | 0.3906      | −0.1371             | 0.4025  | 0.5327|

Regression: 147.5834 14 10.5417 F = 10.86219 0.0001

Residual: 20.3803 21 0.9705

Lack of fit: 19.9954 10 1.9995 F1 = 57.14589 0.0001

Error: 0.3849 11 0.035

Sum: 167.9637 35
Table 7. The 30–40 cm Mc statistical analysis and analysis of variance results.

| Factors | Sum of Squares | Degree of Freedom | Mean Square | Partial Correlation | F-Ratio | P   |
|---------|----------------|-------------------|-------------|---------------------|---------|-----|
| Z1      | 24.9492        | 1                 | 24.9492     | −0.8376             | 49.3765 | 0.0001 |
| Z2      | 67.0338        | 1                 | 67.0338     | −0.9292             | 132.6653| 0.0001 |
| Z3      | 8.9426         | 1                 | 8.9426      | −0.6763             | 17.6981 | 0.0004 |
| Z4      | 0.0925         | 1                 | 0.0925      | −0.093              | 0.1831  | 0.6731 |
| Z12     | 1.2813         | 1                 | 1.2813      | 0.3282              | 2.5359  | 0.1262 |
| Z22     | 3.3822         | 1                 | 3.3822      | 0.4916              | 6.6936  | 0.0172 |
| Z32     | 4.4377         | 1                 | 4.4377      | −0.543              | 8.7826  | 0.0074 |
| Z42     | 2.858          | 1                 | 2.858       | 0.4606              | 5.6563  | 0.027 |
| Z1Z2    | 0.5006         | 1                 | 0.5006      | 0.2122              | 0.9906  | 0.3309 |
| Z1Z3    | 0.6521         | 1                 | 0.6521      | −0.2406             | 1.2905  | 0.2688 |
| Z1Z4    | 1.9113         | 1                 | 1.9113      | −0.3907             | 3.7826  | 0.0653 |
| Z2Z3    | 0.015          | 1                 | 0.015       | 0.0376              | 0.0297  | 0.8648 |
| Z2Z4    | 3.3948         | 1                 | 3.3948      | −0.4923             | 6.7186  | 0.017 |
| Z1Z2Z3  | 0.1351         | 1                 | 0.1351      | −0.1121             | 0.2673  | 0.6106 |
| Regression | 119.5862    | 14               | 8.5419      | F2 = 16.90505       | 0.0001  |
| Residual | 10.611        | 21               | 0.5053      | F1 = 108.22336      | 0.0001  |
| Lack of fit | 10.5042     | 10               | 1.0504      |                     |         |
| Error   | 0.1068         | 11               | 0.0097      |                     |         |
| Sum     | 130.1972       | 35               |             |                     |         |

4. Discussion

4.1. Burial Depth of RPF

The burial depth of RPF had little effect on the Mc, As, and soil Mc (P < 0.01), and had no significant effect on the results. However, some studies have pointed out that the burial depth of RPF in the soil had a large influence on the water infiltration wetting front [41], and there was a significant difference between the movement of the wetting front in the 0–10 and 10–20 cm soil layers [42]. This might be due to the fact that the water head is subject to a certain gravity effect under a certain water head (the constant water head was 6 cm in the present study), and the infiltration process occurs under a state of constant soil air pressure. The Mc was rapid, with the slowest time being 720 min when the wetting front moved down to 40 cm, with the result that there was no significant effect of the burial depth of RPF on the Mc. Due to the small range of RPF values (0–200 kg/hm²) and the fast infiltration rate, the burial depth of RPF did not significantly affect the soil Mc and As. Therefore, in the planting area where the infiltration rate of the water is faster, the influence of the buried depth of the residual film on the infiltration can be ignored for the time being.

4.2. The RPF C

When the RPF was <51 kg/hm², the Mc decreased with the increase in RPF, which was conducive to the downward movement of water. When the RPF was greater than 51 kg/hm², the Mc increased with the increase in RPF, which had a blocking effect on the downward movement of the wetting front in the soil [16]. Most previous studies have shown that the RPF only had a blocking effect on water transport. In the present study, when the RPF was <51 kg/hm², the distribution of RPF in the soil was relatively scattered, and RPF was present in various forms such as sheets, rods, balls, and cylinders. When water flowed over the RPF, the smooth surface of the plastic film formed a smooth diversion surface, enabling water to move rapidly downward. When the RPF was >51 kg/hm², there were many molecular chain branches within the RPF. After encountering water, the adsorption capacity of the adjacent RPF increased, reducing the number of rapid water transport channels and the cross-sectional area of the soil water. The air pressure of the interface between RPF and soil particles increased with the increase in the amount of infiltration water [43]. A narrow wet area could then easily form at the front of the RPF due to the presence of the different large non-uniform flow fields. The soil in the wet area could not achieve a water balance with other areas, in which a water balance is driven by the matrix potential in the short-term. This reduced the driving effect of the matrix
potential on the soil water and enhanced the blocking effect of the RPF on soil water movement. This observation was similar to the results of previous studies obtained by adding other mulches.

The relationship between the RPFC and Ai was described by a parabola (a < 0). When the RPFC was 53 kg/hm², Ai reached its maximum value. This was because when the RPFC was less than 53 kg/hm², the water transfer rate was faster with an increase in the RPFC, which led to a gradual increase in Ai. When the RPFC was >53 kg/hm², the RPF formed an isolation layer in the soil, which destroyed the uniformity of the soil texture and its configuration, changed the soil water potential at the interface between the RPF and the soil, reduced the number of macropores in the soil, and reduced the soil water carrying capacity. As a result, the blocking effect of RPF on the horizontal movement of soil water gradually increased, and then Ai gradually decreased with an increase in RPFC.

The results show that the water content of each soil layer (0–10, 10–20, 20–30, 30–40cm) could be described by a parabolic relationship with the RPFC, where $\alpha < 0$, with maximum values of 74, 68, 71, and 59 kg/hm², respectively. When the RPFC was 50–100 kg/hm², the water content of each soil layer reached a maximum. There may be some experimental error in this test because when the water content of each layer was at a maximum the maximum RPFC was not consistent, but all values were within the range of 50–100 kg/hm².

4.3. The IMC and DBD

With an increase in the IMC, the Mr, Ai, and soil Mc all decreased linearly. This was because the higher the IMC of the soil, which could degrade the effectiveness of soil infiltration and permeability [12], resulting in less Ai. For the same infiltration time less water was able to infiltrate soils with a higher IMC, and therefore, the Mr was shorter and the water Mc decreased accordingly.

The DBD of the soil was positively correlated with the Mr, and negatively correlated with Ai and Mc. This was because the larger the DBD, the smaller the pores between the soil particles, the greater the blocking effect on soil water migration, and fewer water molecules can be contained in the soil. The DBD was therefore positively related to the Mr and negatively related to the Ai and Mc. However, with an increase in the DBD, the porosity of the soil decreased and the influence of DBD on soil infiltration was reduced. This resulted in a decrease in the advance of the wetting front.

4.4. Interaction Effects Between Two Factors

The analysis of the interaction between two factors showed that when the DBD of soil was <1.29 g/cm³, with an increase in the RPFC the Mr increased. When the DBD of soil was >1.29 g/cm³, with an increase in the RPFC, the Mr initially decreased and then increased. When the DBD was >1.31 g/cm³, the Ai initially increased and then decreased with an increase in the RPFC. When the DBD was <1.31 g/cm³, the Ai decreased linearly with an increase in the RPFC. This was because the soil DBD was small and the soil porosity was large, with the shape of the RPF being more irregular in soil with a small DBD than in soil with a large DBD. The RPF isolation layer destroyed the capillary connectivity of the soil, blocked the continuity of the soil pore connectivity and the water transmission capacity, reduced the vertical infiltration capacity of the soil water, and caused the soil water movement to slow down, which influenced the Ai. When the DBD was large and the RPFC was small, the soil porosity was small, and a dense blocking layer formed between the soil particles. A lower RPFC could form a surface to guide the flow of water, which would promote the infiltration of soil water and reduce the Mr, which would lead to an increase in the Ai. When the RPFC was <100 kg/hm², the Mr increased with the increase of DBD. When the RPFC was more than 100 kg/hm², the Mr changed to a lesser extent with the increase in RPFC. This was because when the RPFC was large, the DBD of the soil was low and the RPF had a blocking effect on soil water movement. When the DBD of the soil increased the adsorption capacity between adjacent pieces of RPF decreased, but still had a guiding role.

This study analyzed the influence of various factors on the Mr, Ai, and Mc. These three factors were all fixed to zero for analysis, while the IMC was 11%, the DBD of the soil was 1.35 g/cm³, and the RPFC was 100kg/hm². Through an analysis of the interaction effect between two factors, it was found that changes in the DBD and RPFC had a certain influence on the result when the magnitude of the factors was fixed to zero. Through the above analysis, it was determined that the RPF not only had a
blocking effect on water movement, but also had a diversion effect. The influence of the R_{PFC} on soil water movement was determined through the simulation of 1 × 2 cm rectangular pieces of R_{P}; hence, ignoring the actual differences in the shape and size of R_{P}. In future studies, the influence of the size and shape of R_{P} on soil hydrodynamic properties should be considered.

5. Conclusions

In arid and semi-arid areas, the amount of R_{P} used as a mulch in farmland is increasing annually. The amount of R_{P} in the soil is also increasing annually. The R_{P} retained in the soil causes “white pollution” and damages the environment. In this experiment, the surface soil of Yangling was used to determine the effect of residual film on one-dimensional soil infiltration. Found that when the R_{PFC} was 50–100 kg hm\(^{-2}\), the R can reach a minimum value, and the soil Mc and Ai can reach a maximum value. There may be a certain error in the test, resulting in R_{PFC} in the range of 50–100 kg hm\(^{-2}\). Therefore, it is proposed that the R_{PFC} should be controlled to be below 50 kg/hm\(^{2}\) when the R_{P} is recovered after agricultural operations. This study can provide a reference for reasonable irrigation in residual film area.

In the future studies, the choice of soil should be more extensive to understand the effect of R_{PFC} on infiltration. The relationship between various physiological indexes of crops and R_{PFC} should also be studied to establish a model of R_{P} and crops yield to provide advice for the cultivation of residual film area.

Supplementary Materials: The following are available online at www.mdpi.com/2073-4441/12/5/1346/s1, Table S1: Quadratic regression orthogonal design and experimental results.

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