Research Article
Multifunctional Superabsorbent Polymer under Residue Incorporation Increased Maize Productivity through Improving Sandy Soil Properties

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Superabsorbent polymer (SAP) is a new water-retaining and nutrient-holding material with the potential to improve soil properties and promote crop growth in arid and semiarid areas. This study investigated the effects of multifunctional SAP on the sandy soil properties and maize productivity in Yanghuang irrigated area of Ningxia where residue incorporation was a common agricultural practice. We tested multifunctional SAP at different doses of 0, 30, 60, 90, and 120 kg ha$^{-1}$ under the residue incorporation to the field. The soil bulk density in the 0–0.40 m layer was significantly lower by 6.2–8.2% under SAP at 60–120 kg ha$^{-1}$ compared with no SAP, but the total soil porosity was improved significantly by 8.5–11.2%, where the SAP at 90 and 120 kg ha$^{-1}$ had the greatest effects. The applications of SAP at 60 and 90 kg ha$^{-1}$ significantly improved soil organic matter, and available $P$ and $K$ contents in the 0–0.40 m soil layer. The soil water storage (0–1.0 m) under SAP at 60–120 kg ha$^{-1}$ was significantly increased by 17.1–18.7% compared with no SAP throughout the whole maize growing season. The SAP at 60–90 kg ha$^{-1}$ significantly promoted crop growth and maize yield formation, and increased grain yield, whereas the net income were the highest with applying SAP at 30–60 kg ha$^{-1}$. In combination with the soil physicochemical property, crop productivity and economic benefit comprehensive analysis of this two-year study, we recommended that the application of multifunctional SAP at 30–60 kg ha$^{-1}$ under residue incorporation significantly improved the sandy soil properties, as well as increasing maize growth, crop productivity, and obtain the higher net income for farmers in Yanghuang irrigation area of Ningxia, China.

1. Introduction

In the dryland farming region of northern China, maize ($Zea mays$ L.) is the main grain and forage crop, and the area planted with maize is growing more rapidly than that with other crops. The yield of maize accounts for about half of the total grain production in Ningxia and it is the highest of all the grain-producing crops [1]. Therefore, improving maize productivity is very important for ensuring food security in Ningxia. The abundant light and heat resources in the Yanghuang irrigation area of Ningxia are advantageous for maize productivity [2]. However, the planting of maize in this area is affected by water shortages and by the soil type, which is dominated by the gray-calcium soil formed under the desert steppe vegetation type. Thus, soil infertility and water deficiency are major constraints on maize productivity in this region [3].

Water-saving techniques have been developed to overcome the challenges caused by the limited availability of water resources for agriculture [4]. Among the many water-saving techniques that have been developed, the use of chemical water-saving materials is important for facilitating water-saving agriculture in arid areas [5, 6]. Superabsorbent polymers (SAPs) have been developed as chemical water-saving agents and applied widely [7]. SAPs are hydrophilic network polymers with a super-high capacity for water absorption and retention, and a slow water release [8]. Previous studies have shown that the application of SAPs to soils can reduce the water evaporation from the soil surface and water infiltration [9], and the soil porosity and
structural stability can also be improved [10]. Meanwhile, SAPs also can improve the conservation of soil water, prevent deep percolation and soil nutrient losses, and maximize the water and fertilizer use efficiency [6, 11]. Maize belonged to the crop with high water consumption, whereas SAPs have the stronger effect on increasing maize productivity [12, 13]. Recently, most commoditized polymers are mainly in polypropylene acid (PAA) or polycrylamide (PAM), but the high prices of SAPs limits its applications in agriculture [14]. Attapulgite and other clay minerals are incorporated in SAPs to reduce production cost, and also to improve the properties (e.g., swelling ability, gel strength, and mechanical and thermal stability) of the SAPs (e.g., organic–inorganic hybrid multifunctional SAP) [15, 16]. Thus, the application of multifunctional SAP in agriculture has become a popular water-saving technology for farmers in arid and semi-arid regions of northern China.

Droughts occur often in the Yanghuang irrigation area of Ningxia, where the infertility of the sandy soils and severe losses of water and fertilizer greatly affect the growth and development of maize [3]. Returning crop residue to the field is an important practice for enhancing crop production with a favorable soil environment [17], as well as alleviating the soil degradation caused by intensive and continuous conventional tillage [18]. The beneficial effect on water and nutrient holding capacity by adding multifunctional SAP to sandy soils has been well documented in short-time lab studies [19, 20]. However, less is known about its performances under repeated cycles of irrigation and residue incorporation in the field. In field applications, SAPs are also affected by environmental conditions, such as the soil temperature, humidity, microbes, and soil wetting and drying cycles [5, 11, 21]. Many studies on SAPs for use in agriculture have focused on the research and development of new materials and products [22, 23], the comparison and evaluation of physical and chemical characteristics [24, 25], and the effects on soil and plant growth [8, 26]. Combining the water and fertilizer conservation functions of multifunctional SAP with the soil fertility improvements obtained by residue incorporation to the soil under the drip irrigation condition in order to enhance the soil properties and agricultural production has important practical significance, especially for improving sandy soil with the bulk density over 1.5 kg cm$^{-3}$ and the organic matter below 5.0 g kg$^{-1}$ in the Yanghuang irrigation area. However, few studies have considered the effects of multifunctional SAP on improving the sandy soil properties and maize productivity when residue is returned to sandy soil in irrigated areas. Thus, in the present study, we conducted a continuous two-year field experiment to determine the application effects of multifunctional SAP different doses combined with the return of residue to the soil on the physical and chemical properties of the soil, as well as the growth, and crop productivity for maize. We tested multifunctional SAP at different application rates, and the multifunctional SAPs were mixed with air-dried soil and used by spot application around the root during the maize seedling stage. The main objective of this study was to clarify the soil amelioration and fertility effects and maize productivity of applying multifunctional SAPs at different rates. Our results should provide a reference to support the rational application of multifunctional SAPs to enhance the fertility of sandy soil and maize productivity under conditions with the residue incorporation to the soil in Yanghuang irrigation area of Ningxia, China.

2. Materials and Methodology

2.1. Site Description. This study was conducted between 2015–2017 in Sandunzi Village, Yanchi County, Ningxia Province (37°40’N, 106°51’E), which is located in eastern Ningxia. The study site was a typical Yanghuang irrigation area with an average elevation of 1300 m. The experimental site was located in a warm temperate zone with an annual mean air temperature of 9.4°C. The mean annual precipitation was 280 mm, where it mainly occurred during June–September, and the average annual pan evaporation was about 2500 mm. The total annual sunshine was 2800 h and the frost-free period was 151 days. Weather data were obtained from a weather station at the experimental site. The monthly precipitation and air temperature distributions during the experimental period are shown in Figure 1. The precipitation rates during the maize growing season (April–September) were 224.2 and 184.8 mm in 2016 and 2017, respectively.

Reclaiming virgin land and plowing cropland in the experimental area destroy soil structure and accelerate the loss of soil organic carbon, the top layer of the original sierozem was covered by deep aeolian sandy soil. The upper layer of the soil (0–0.40 m) was sandy loam and the lower layer (0.40–1.0 m) was light sierozem [3]. The physical and chemical properties at the 0–1.0 m soil depth are shown in Table 1. The soil was classified according to the United States Department of Agriculture (USDA) Soil Texture Classification Standard [27, 28]. The topsoil (0–0.40 m) at the experimental site had the following characteristics (Table 1): soil bulk density 1.54 g cm$^{-3}$, total salt 0.43 g kg$^{-1}$, organic matter 4.7 g kg$^{-1}$, available N 35.2 mg kg$^{-1}$, available P 4.6 mg kg$^{-1}$, and available K 67.5 mg kg$^{-1}$. The site was sown with spring maize prior to the experiment in 2016.

2.2. Field Management and Experimental Design. Before mixing with the soil, maize residue was chopped into segments with a length of 0.05 m and then applied to the soil at six months before the crop was sown to facilitate residue decomposition. The 9000 kg ha$^{-1}$ maize residue was incorporated into the 0.20 m soil layer on October 7, 2015 and after the crop was harvested during 2016–2017. Before sowing, a basic fertilizer (DAP) at a rate of 300 kg ha$^{-1}$ was spread evenly over each plot and plowed into the soil layer. Maize (cv. Longdan 9 in 2016, Yinyu 439 in 2017) was sown at a rate of 95,250 plants ha$^{-1}$ on April 20, 2016 and April 22, 2017 using an air-suction precision planter. Each treatment had the same row width spacing of 0.70 m and a narrow plant spacing of 0.30 m, and a thin-walled drip irrigation hose was laid near the plant row. Irrigation and fertilizer were applied in the key maize growing period (Table 2). Irrigation water was applied every 10 days after sowing the
maize. A differential pressure tank was connected to the drip irrigation system to inject fertilizer via irrigation. The irrigation frequency and amount during the maize growing season were 12 times and 2400 m³ ha⁻¹. Nitrogen fertilizer was added in the form of urea (N 46%) at a rate of 780 kg ha⁻¹. Potassium sulfate (K₂O 50%) was added at a rate of 165 kg ha⁻¹. Maize was harvested on September 28, 2016 and September 30, 2017.

SAPs have different effects on the soil porosity and crop production according to their type, application method, and application dose [21]. Previous studies have shown that the application of SAP at 60 kg ha⁻¹ and a depth of 0.20 m significantly improved crop growth and yield, and this method is recommended for oil sunflower cultivation in the arid area of central Ningxia [29]. However, the use of a multifunctional SAP at 30 kg ha⁻¹ at the seeding stage is more suitable for potato production in the mountainous area of south Ningxia [30]. In order to determine the application effects of multifunctional SAP doses on the soil properties and maize productivity under the residue incorporation conditions in Yanghuang irrigation area, this experiment tested multifunctional SAP, Wote SAP as an organic-inorganic hybrid SAP, consists of a negatively charged acrylic-acrylamide polymer synthesized with an attapulgite (composition: 70% negatively charged acrylic-acrylamide polymers with 20% hydrolysis synthesized with 30% attapulgite; water absorptivity = 500 – 600 g g⁻¹; bead size =0.4–1.5 mm; pH = 6.0 – 8.0; and life span = 3 – 5 years; manufactured from polyacrylamide and acrylic acid by Dongying Huaye New Material Co., Ltd., in Shandong) at different application rates.

According to the recommended dosage of the Wote SAPs from the manufacturers and the former studies, the five treatments tested in this study comprised: SAP 0 kg ha⁻¹ (SAP0), SAP 30 kg ha⁻¹ (SAP30), SAP 60 kg ha⁻¹ (SAP60), SAP 90 kg ha⁻¹ (SAP90), and SAP 120 kg ha⁻¹ (SAP120). Each treatment comprised three replicated plot and each plot measured 12 m long × 10.0 m wide. The multifunctional SAP was evenly mixed with air-dried soil before its application at different rates. To combat drought and protect the seedlings, spot application around the root under normal farming conditions was often used in maize production of seedling stage. The SAP was added to the soil at the maize five-leaf stage at the depth with root development by making 0.20 m deep holes in the soil. A 0.15 m soil–SAP mixed layer was placed 0.20 m below the soil surface. The holes were filled with a mixture of soil and SAP. Soil was compacted around the roots manually. Manual weeding was performed as required throughout the experiment.

2.3. Sampling and Analysis. Immediately after the harvest in 2015 and 2017, three random soil samples were collected.
Table 1: Physical and chemical properties at the 0–1.0 m soil depth in the experimental site.

| Depth cm | Sand (%) 2.0-0.05 mm | Silt (%) 0.05-0.005 mm | Clay (%) <0.005 mm | Classification | BD (g cm⁻³) | OM (g kg⁻¹) | TS (g kg⁻¹) | AN (mg kg⁻¹) | AP (mg kg⁻¹) | AK (mg kg⁻¹) | pH |
|----------|----------------------|------------------------|-------------------|---------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-----|
| 0-40     | 69.8                 | 19.6                   | 10.6              | Sandy loam    | 1.54        | 4.7         | 0.43        | 35.2        | 4.6         | 67.5        | 8.8 |
| 40-100   | 56.2                 | 30.4                   | 13.4              | Light sierozem| 1.44        | 2.3         | 0.64        | 18.8        | 1.8         | 28.0        | 9.3 |

BD, bulk density; OM, organic matter; TS, total salt; AN, available nitrogen; AP, available phosphorus; AK: available potassium.
from the middle of two planting rows in each plot using a 54 mm diameter steel core sampling tube, which was driven manually to depths of 0.20 m and 0.40 m. The soil cores were weighed wet, dried at 105°C for 48 h, and weighed again to determine their bulk density [31].

Soil samples were collected from two depths (0–0.20 and 0.20–0.40 m) in each treatment after the maize harvest in 2015 and 2017. A soil sample was taken from each plot to determine the soil nutrient indexes. Soil organic matter was determined using the H2SO4–K2Cr2O7 oxidation method [32]. Available N was analyzed using the cadmium reduction method [33]. Available P was extracted with a NaHCO3 solution adjusted to pH 8.5 [32]. Available K was determined by flame photometry [34].

The soil water content was determined in the middle of two planting rows in each plot seven times during the season before irrigation by collecting three random soil core samples from the middle of two planting rows in each plot using a 54 mm diameter steel core sampling tube, which was driven manually to a depth of 1.0 m during each maize growing season. The stems and leaves of five plants were measured to determine their fresh mass, before drying in an oven at 105°C for 1 h and then at 75°C for at 72 h to obtain the dry mass.

The following yield components were measured at the maize maturity stage between 2016 and 2017: heads per square meter, kernels per head, and 100 kernel weight. Heads per square meter were determined using 3 square meter area (1.0 m × 3.0 m) for each treatment with three replicates in each plot. Kernels per harvested area were calculated by dividing the harvested grain weight by the number of heads per harvested area. After oven drying and weighing, grain was threshed from the straw, cleaned, and weighed. Weights per kernel were measured by counting and weighing 100 kernel samples taken from the harvested grain of each plot. The maize grain yield was measured at 12% water content by manually harvesting from a 3 square meter area (1.0 m × 3.0 m) for each treatment with three replicates in each plot.

2.4. Statistical Analysis. The data were analyzed by analysis of variance (ANOVA) using the SAS 8.02 package (SAS Institute Inc., North Carolina, USA). The significance of F values was determined from ANOVA tables. Multiple comparisons of the annual mean values were performed using Duncan’s multiple range tests. In all of the analyses, P < 0.05 was considered to indicate a significant difference. Graphs and tables were prepared using Excel 2003.

3. Results and Discussion

3.1. Soil Physicochemical Characteristics. SAPs can change the soil basic physical properties because of their strong water-absorbing capacity and changes in volume during wetting and drying cycles [5]. Proper use of SAP could
reduce the soil bulk density, improve the soil permeability, and could help superfluous organic matter aggregate into the soil layer, so as to prevent it being immediately decomposed or lost [36]. Before the experiment (in 2015), the mean soil bulk density in the topsoil (0–0.40 m) was 1.54 g cm$^{-3}$. After the two-year experiment, the soil bulk density in SAP60, SAP90, and SAP120 decreased significantly compared with the initial background value (before treating), whereas it decreased slightly in SAP30 and SAP0 (Table 3). The mean soil bulk densities with SAP60, SAP90, and SAP120 decreased significantly ($P < 0.05$) by 6.2%, 7.6%, and 8.2% compared with SAP0, respectively. The soil total porosities in all the treatments increased significantly compared with the pretreatment level (Table 3). The soil total porosities in SAP60, SAP90, and SAP120 were 8.5%, 10.4%, and 11.2% ($P < 0.05$) than that in SAP0, respectively. Thus, the application of multifunctional SAP significantly increased the soil porosity by maintaining lower bulk density levels in the topsoil (0–0.40 m) compared with no SAP. This was attributed to the fact that applying the multifunctional SAP with topsoil layer could form large numbers of macropores during the water absorption process, and improve the topsoil pore structure [36]. This could have been related to the composition of the multifunctional SAP with the high water absorbency and volume expansibility rate [37]. The difference in root density, soil organic matter contents and the external mechanical forces during SAP fertilization (residue incorporation with superabsorbent polymer) may also the possible reasons. SAP with crop straw and residue under deep ploughing measure were helpful in promoting crop root growth, thus forming the root network, root rot, and root secretion, which led to an enhancement in root density, soil organic matter and available K contents by 36.1%, 48.6%, and 21.9%, respectively. First, residue incorporation could effectively improve the soil fertility, increase the contents of organic matter and total nitrogen to some extent, and improve the soil fertility conservation and supply capacity [42]. Second, the application of multifunctional SAPs could improve the sandy soil physicochemical properties [43], and facilitated the transformation of fertilizers or soil nutrients into a slowly available nutrient source, thereby preventing the immediate decomposition or loss of nutrients [36]. Third, the suitable concentrations of SAP can absorb more water, nutrients can be released slowly, and nutrient retention in topsoil can be increased [6, 42]. Also, excessive application of SAP (SAP at 90 and 120 kg ha$^{-1}$) could also cause the soil structure to be hardened and the soil quality to be reduced [43, 44], which may result in lower microbial activity [39] and the decreased soil organic matter and available N contents.

3.2. Soil Water Storage. The application of SAP could affect the soil water retention, migration, and redistribution [45]. Due to differences in precipitation, irrigation, and the multifunctional SAP dose, the soil water storage in the 0–1.0 m layer in all treatments varied greatly during the maize growing season, but they tended to fluctuate less as the growth of the maize continued (Figure 2). The soil water storage was the same (data not shown) in each treatment before the application of multifunctional SAP at 25 DAS. The SAP treatments significantly improved the soil water storage at 50 DAS compared with no SAP. The soil water storage with SAP90 and SAP120 in 2016 were 18.4% and 21.7% ($P < 0.05$) higher compared with SAP0. In 2017, the SAP30, SAP60, SAP90, and SAP120 treatments improved the soil water storage by 18.3%, 21.7%, 16.1%, and 10.6% ($P < 0.05$) at 50 DAS, when compared with SAP0, respectively.

During the middle growing stage (from 75–100 DAS), the soil water storage decreased sharply in each treatment as maize growth entered a vigorous period and the consumption of water by the crop increased (Figure 2). In 2016, the soil water storage was increased significantly higher in the SAP treatments. At 75 DAS, the SAP90 and SAP120 treatments significantly ($P < 0.05$) increased the soil water storage by 20.1% and 22.4% compared with SAP0, and the soil water storage with SAP60, SAP90, and SAP120 were 16.2%, 19.9%, and 27.3% higher ($P < 0.05$) compared with SAP0 at 100 DAS. During 2017, the SAP30, SAP60, and SAP90 treatments significantly ($P < 0.05$) increased the soil water storage by 22.2%, 27.7%, and 22.9% from 75–100 DAS compared with SAP0, respectively.
Therefore, the soil water storage with SAP at 60–120 kg ha\(^{-1}\) was compared with SAP0, followed by SAP90 and SAP120 with storage with SAP60, SAP90, and SAP120 were 12.4%, and increased the soil water content, where the soil water storage increased with SAPs applying in a certain range [46], whereas excessive or low doses failed to achieve beneficial effects [11, 37, 47].

### Table 3: Effects of multifunctional SAP doses on soil physicochemical characteristics in 0–0.40 m layer.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Soil bulk density (g cm(^{-3}))</th>
<th>Total porosity (%)</th>
<th>Soil organic matter (g kg(^{-1}))</th>
<th>Soil available N (mg kg(^{-1}))</th>
<th>Soil available P (mg kg(^{-1}))</th>
<th>Soil available K (mg kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before treating</td>
<td>1.54 ± 0.02a</td>
<td>41.89 ± 1.53c</td>
<td>4.70 ± 0.15a</td>
<td>35.20 ± 1.12a</td>
<td>4.60 ± 0.34ab</td>
<td>67.50 ± 2.74a</td>
</tr>
<tr>
<td>SAP0</td>
<td>1.53 ± 0.02b</td>
<td>42.30 ± 1.28bc</td>
<td>4.07 ± 0.07c</td>
<td>22.51 ± 1.21b</td>
<td>5.02 ± 0.13c</td>
<td>55.95 ± 3.62c</td>
</tr>
<tr>
<td>SAP30</td>
<td>1.49 ± 0.01b</td>
<td>43.66 ± 0.31b</td>
<td>4.51 ± 0.14bc</td>
<td>26.65 ± 0.88b</td>
<td>6.83 ± 0.36ab</td>
<td>78.14 ± 2.85ab</td>
</tr>
<tr>
<td>SAP60</td>
<td>1.43 ± 0.04c</td>
<td>45.89 ± 1.09a</td>
<td>5.47 ± 0.08a</td>
<td>34.21 ± 0.84a</td>
<td>7.46 ± 0.43a</td>
<td>84.88 ± 3.72a</td>
</tr>
<tr>
<td>SAP90</td>
<td>1.41 ± 0.03c</td>
<td>46.68 ± 1.05a</td>
<td>5.10 ± 0.16a</td>
<td>28.65 ± 1.35ab</td>
<td>6.12 ± 0.38bc</td>
<td>89.09 ± 4.08a</td>
</tr>
<tr>
<td>SAP120</td>
<td>1.40 ± 0.02c</td>
<td>47.02 ± 0.70a</td>
<td>4.31 ± 0.10bc</td>
<td>24.48 ± 0.98b</td>
<td>5.36 ± 0.29c</td>
<td>80.08 ± 3.96a</td>
</tr>
</tbody>
</table>

SAP0 = SAP0 kg ha\(^{-1}\); SAP30 = SAP 30 kg ha\(^{-1}\); SAP60 = SAP 60 kg ha\(^{-1}\); SAP90 = SAP 90 kg ha\(^{-1}\); and SAP120 = SAP 120 kg ha\(^{-1}\). Values followed by the same lowercase letter in the same column are not significant according to the least significant different test (LSD 0.05).

**Figure 2:** Effects of multifunctional SAP doses on soil water storage (0–1.0 m) during the maize growing season in 2016–2017. SAP0 = SAP0 kg ha\(^{-1}\); SAP30 = SAP 30 kg ha\(^{-1}\); SAP60 = SAP 60 kg ha\(^{-1}\); SAP90 = SAP 90 kg ha\(^{-1}\); and SAP120 = SAP 120 kg ha\(^{-1}\). Horizontal bars represent significant difference at the 0.05 probability level according to the least significant different test (LSD 0.05).

During the later growth stage (from 125–150 DAS), there was an increase in rainfall and a decrease in crop water use, and the soil water storage increased in each treatment (Figure 2). In 2016, the SAP treatments improved the soil water storage at 150 DAS, especially the average soil water storage with SAP60, SAP90, and SAP120 were 12.4%, 14.3%, and 17.7% higher (\(P < 0.05\)), respectively, compared with SAP0. In 2017, the SAP60 treatment obtained the best effect of water-holding capacity (20.2%) at 150 DAS compared with SAP0, followed by SAP90 and SAP120 with 19.9% and 15.1% higher (\(P < 0.05\)) than SAP0, respectively, Therefore, the soil water storage with SAP at 60–120 kg ha\(^{-1}\) throughout the entire maize growing season was significantly increased compared with no SAP. This was because an appropriate range of SAP doses could have improved the soil structure and water-holding capacity, stored more water in the soil, and increased the soil water content, where the soil water storage increased with SAPs applying in a certain range [46], whereas excessive or low doses failed to achieve beneficial effects [11, 37, 47].

3.3. **Crop Growth.** The application of SAP could conserve the soil water and make it available to plants to allow increased crop growth and biomass accumulation, especially under severe water stress conditions [48]. The maize plant height, stem diameter, and aboveground biomass were affected by multifunctional SAP applying, as shown in Figure 3. The mean plant heights in SAP60 and SAP90 were 13.2% and 12.1% higher (\(P < 0.05\)) than that in SAP0, respectively, during the whole growth stage. However, there were no significant differences in the plant height between SAP30, SAP120, and SAP0 at 50 DAS and 150 DAS. The maize stem
Figure 3: Maize plant height, stem diameter, and aboveground biomass under multifunctional SAP doses during the maize growing season in 2016–2017. SAP0 = SAP 0 kg ha\(^{-1}\); SAP30 = SAP 30 kg ha\(^{-1}\); SAP60 = SAP 60 kg ha\(^{-1}\); SAP90 = SAP 90 kg ha\(^{-1}\); and SAP120 = SAP 120 kg ha\(^{-1}\). Horizontal bars represent significant difference at the 0.05 probability level according to the least significant different test (LSD 0.05).
diameters in SAP30, SAP60, and SAP90 were 10.7%, 17.0%, and 11.3% higher \( (P < 0.05) \) than that in SAP0, respectively, during the whole growth period. The aboveground biomass in SAP60 was significantly \( (P < 0.05) \) higher than that in SAP0 during the whole growth period. At 50 DAS, the SAP60, SAP90, and SAP120 treatments increased the aboveground biomass by 70.8%, 54.2%, and 43.8% \( (P < 0.05) \), respectively, compared with the SAP0 treatment. At 75 DAS, the aboveground biomass in SAP60 was 76.8% higher \( (P < 0.05) \) that in SAP0. At 100–125 DAS, the mean aboveground biomass in SAP60 and SAP90 was 56.4% and 52.8% higher \( (P < 0.05) \) than that in SAP0, respectively. At 150 DAS, the aboveground biomass in SAP60, SAP90, and SAP120 was 51.4%, 48.2%, and 45.7% higher \( (P < 0.05) \) than that in SAP0, respectively.

During 2017, the maize plant height and stem diameter in the multifunctional SAP treatments were significantly higher than those in no SAP treatment during the whole growth period, and the SAP60 and SAP90 treatments had the most significant improvement effects. The plant heights in SAP60, SAP90, and SAP120 were 18.9%, 20.4%, and 13.7% higher \( (P < 0.05) \) than those in SAP0, respectively, and the stem diameters were 15.2%, 18.6%, and 13.5% higher \( (P < 0.05) \). The SAP60 and SAP90 treatments had the most significant effects on the maize aboveground biomass during the whole growth period, followed by SAP120 and SAP30. There were no significant differences in the aboveground maize biomass between SAP60 and SAP90, and between SAP30 and SAP120, but the aboveground biomass is each SAP treatment was significantly higher than that in SAP0. The maize aboveground biomass in SAP30, SAP60, SAP90, and SAP120 was 23.9%, 66.7%, 58.3%, and 45.0% higher \( (P < 0.05) \) than that in SAP0, respectively. In the present study, the application of multifunctional SAP under conditions where the residue was returned to the soil could promote the growth of maize, and the best effect was obtained when the SAP was applied at 60–90 kg ha\(^{-1}\). This was because residue incorporation had beneficial improvement effects on the soil physical and chemical properties [49], and the appropriate application of SAP improved the soil structure as well as enhancing the absorption and retention of soil nutrients to promote plant growth [50]. However, the effect of the SAP was not obvious when the dosage was excessively low and it inhibited crop growth when the dosage was excessively high [45, 51].

3.4. Maize Productivity and Economic Benefits. Using SAPs could significantly increase the maize yield by enhancing the soil physical properties and crop productivity in arid lands [52]. Under the conditions where residue was returned to the soil, there were significant differences in the maize yield formation (heads, kernels per head, and 100 kernel weight) under the multifunctional SAP application rates, and the applications of SAP60 and SAP90 achieved the best yield productivity in 2-year study (Table 4). During the 2-year study, the numbers of heads per square meter with each SAP treatments was significantly different with no SAP, and the SAP60 treatment was the most significant, which with an average increased by 19.0% \( (P < 0.05) \) compared with SAP0. The kernels per head with SAP60 and SAP90 were increased significantly \( (P < 0.05) \) by 29.7% and 21.5%, followed by SAP120 and SAP30, which were increased by 19.8% and 14.6% \( (P < 0.05) \), respectively, compared with SAP0. The 100 kernel weight with all the treatments were ranked as follows: SAP60 > SAP90 > SAP120 > SAP30 > SAP0, and the 100 kernel weight with SAP60, SAP90, SAP120, and SAP30 was significantly \( (P < 0.05) \) increased by 11.1%, 8.4%, 5.7%, and 5.3%, respectively, compared with SAP0. During 2016, the maize grain yield followed the order of: SAP60 > SAP90 > SAP30 > SAP120 > SAP0. The maize grain yields in SAP30, SAP60, and SAP90 were 26.5%, 41.8%, and 39.8% higher \( (P < 0.05) \) than that in SAP0, respectively, but there was no significant difference between those in SAP120 and SAP0. During 2017, the maize grain yields in all treatments were ranked as follows: SAP60 > SAP90 > SAP120 > SAP30 > SAP0. The maize grain yields in SAP30, SAP60, SAP90, and SAP120 were significantly higher \( (P < 0.05) \) than that in SAP0, but there were no significant differences between those in SAP30, SAP90, and SAP120. The maize grain yields with SAP30, SAP60, SAP90, and SAP120 were 23.5%, 34.5%, 29.1%, and 20.3% higher \( (P < 0.05) \) compared with that in SAP0, respectively, where the SAP60 treatment obtained the most significant effect on increasing maize grain yield. Therefore, the application of multifunctional SAP at 60 kg ha\(^{-1}\) could significantly improve the maize productivity because the application of multifunctional SAP enhanced the absorption and release of water as well as the retention of fertilizer to improve the soil water and nutrient microenvironment for crop growth [5], thereby significantly enhancing the crop productivity. However, the excessive use of SAP (120 kg ha\(^{-1}\)) decreased the crop productivity in our study and the following two possible reasons could explain these results. First, the optimal SAP does is affected by many factors, such as the soil and crop species [8, 53]. Second, if the SAP is applied at an excessive rate, it might compete with the crops for part of the water under drought conditions to increase the drought stress in plants, thereby increasing the membrane permeability and causing damage to affect the yield [13, 54].

There were obvious differences in the input costs for the various treatments because of the requirements for the SAP materials and labor, but the application of SAP obtained improved economic benefit (Table 4). During the two-year study, the input costs for all the treatments were ranked as follows: SAP120 > SAP90 > SAP60 > SAP30 > SAP0. The output values with the different treatments were ranked as follows: SAP60 > SAP90 > SAP30 > SAP120 > SAP0. The net income was the highest with SAP60, followed by SAP30 and SAP90. The mean net incomes with SAP30, SAP60, and SAP90 were 17.5%, 24.7%, and 11.6% higher \( (P < 0.05) \) compared with SAP0, respectively. However, SAP120 significantly \( (P < 0.05) \) decreased the mean net income by 17.0%. In the present study, the application of multifunctional SAP at 60 kg ha\(^{-1}\) was the best since the net income was obviously higher than SAP30. Optionally, the application of SAP at 30 kg ha\(^{-1}\) could be also worthy under situations where input cost is limited. Previous studies also suggested that applying large amounts of SAP to soil was not recommended and that...
Table 4: Crop productivity and economic benefit of maize under multifunctional SAP doses.

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>Heads ($\times 10^4$ ha$^{-1}$)</th>
<th>Kernels per head (no.)</th>
<th>100–Kernel weight (g)</th>
<th>Grain yield (kg ha$^{-1}$)</th>
<th>Input (Chinese yuan ha$^{-1}$)</th>
<th>Output (Chinese yuan ha$^{-1}$)</th>
<th>Net income (Chinese Yuan ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016</td>
<td>SAP0</td>
<td>8.37 ± 0.61c</td>
<td>388 ± 11.7b</td>
<td>34.6 ± 0.98c</td>
<td>7482.0 ± 347.2c</td>
<td>2100</td>
<td>11971.2 ± 472.6d</td>
<td>9871.2 ± 398.2c</td>
</tr>
<tr>
<td></td>
<td>SAP30</td>
<td>8.97 ± 0.20b</td>
<td>383 ± 18.8b</td>
<td>35.3 ± 1.75b</td>
<td>9462.0 ± 276.4b</td>
<td>3400</td>
<td>15139.2 ± 526.1b</td>
<td>11739.2 ± 457.6b</td>
</tr>
<tr>
<td></td>
<td>SAP60</td>
<td>9.86 ± 0.29a</td>
<td>430 ± 7.4ab</td>
<td>36.4 ± 0.94ab</td>
<td>10612.5 ± 301.9a</td>
<td>4300</td>
<td>16980.0 ± 499.6a</td>
<td>12680.0 ± 412.8b</td>
</tr>
<tr>
<td></td>
<td>SAP90</td>
<td>8.88 ± 0.32b</td>
<td>445 ± 35.6a</td>
<td>37.2 ± 0.52a</td>
<td>10456.5 ± 415.3ab</td>
<td>5200</td>
<td>16730.4 ± 512.3ab</td>
<td>11530.4 ± 384.9b</td>
</tr>
<tr>
<td></td>
<td>SAP120</td>
<td>8.86 ± 0.25b</td>
<td>443 ± 15.6a</td>
<td>35.3 ± 1.02b</td>
<td>8521.5 ± 368.0bc</td>
<td>6100</td>
<td>13634.4 ± 422.4c</td>
<td>7534.4 ± 382.6d</td>
</tr>
<tr>
<td>2017</td>
<td>SAP0</td>
<td>7.67 ± 0.12d</td>
<td>454 ± 25.8c</td>
<td>35.4 ± 0.76c</td>
<td>8383.4 ± 315.8c</td>
<td>2100</td>
<td>13413.4 ± 389.0c</td>
<td>11313.4 ± 342.8c</td>
</tr>
<tr>
<td></td>
<td>SAP30</td>
<td>8.55 ± 0.23c</td>
<td>582 ± 29.2b</td>
<td>38.4 ± 0.55b</td>
<td>10350.8 ± 384b</td>
<td>3400</td>
<td>16561.3 ± 458.2b</td>
<td>13161.3 ± 415.4b</td>
</tr>
<tr>
<td></td>
<td>SAP60</td>
<td>9.22 ± 0.38a</td>
<td>662 ± 14.4a</td>
<td>41.4 ± 0.79a</td>
<td>11277.5 ± 308.1a</td>
<td>4300</td>
<td>18044.0 ± 474.6a</td>
<td>13744.0 ± 426.3a</td>
</tr>
<tr>
<td></td>
<td>SAP90</td>
<td>8.97 ± 0.32b</td>
<td>578 ± 23.8b</td>
<td>38.7 ± 0.66b</td>
<td>10820.2 ± 391.6b</td>
<td>5200</td>
<td>17312.3 ± 388.7b</td>
<td>12112.3 ± 323.4b</td>
</tr>
<tr>
<td></td>
<td>SAP120</td>
<td>8.67 ± 0.30c</td>
<td>566 ± 32.6b</td>
<td>38.7 ± 0.45b</td>
<td>10090.7 ± 298.8b</td>
<td>6100</td>
<td>16145.1 ± 436.4b</td>
<td>10045.1 ± 411.6c</td>
</tr>
</tbody>
</table>

The price of maize was 1.6 Chinese Yuan kg$^{-1}$; SAP price was 30 Chinese Yuan kg$^{-1}$; Labour cost was 400 Chinese Yuan ha$^{-1}$; seed and fertilizers costs were 600 Chinese Yuan ha$^{-1}$, and drip irrigation materials costs were 1500 Chinese Yuan ha$^{-1}$. Net income (CNY ha$^{-1}$) = Output value – Input value. Where Output value = Maize grain yield × Market price. Input value of SAP treatments = Labor costs + SAP costs + Seed and fertilizer costs + Drip irrigation materials costs. However, Input value of CK = Seed and fertilizer costs + Drip irrigation materials costs + Tractor farming fee (tillage, residue incorporation, and harvesting). SAP0 = SAP 0 kg ha$^{-1}$; SAP30 = SAP 30 kg ha$^{-1}$; SAP60 = SAP 60 kg ha$^{-1}$; SAP90 = SAP 90 kg ha$^{-1}$; and SAP120 = SAP 120 kg ha$^{-1}$. Values followed by the same lowercase letter in the same column are not significant according to the least significant different test (LSD 0.05).

farmers should consider the input cost, absorption characteristics, and the actual effects of applying SAPs. Further studies of these effects are required.

4. Conclusions

The results of our 2-year study showed that the application of multifunctional SAP under the residue returning conditions effectively reduced the bulk density, improved the soil total porosity, and increased the soil organic matter and available nutrient contents in the topsoil (0–0.40 m) compared with no SAP. The applications of SAP at 60 and 90 kg ha$^{-1}$ had the greatest effects on the improvements in soil physicochemical characteristics, and they significantly promoted maize growth. The applications of SAP at 60 and 90 kg ha$^{-1}$ significantly increased the maize productivity (yield formation and grain yield) compared with no SAP, whereas the net income were the highest with applying SAP at 30–60 kg ha$^{-1}$. Based on the improved properties of the sandy soils, maize growth, productivity, and economic benefits, farmers could be recommended to use multifunctional SAP 30–60 kg ha$^{-1}$ to improve the physical and chemical properties of sandy soils, and increase maize productivity and obtain the higher net income. It was potentially possible to use the method under the condition in an irrigated area of northwest China where residue incorporation was common agricultural practice.

Data Availability

The data used to support the findings of this study are included within the article. Further data or information is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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