

Article

Effect of Furrow Straw Mulching and Straw Decomposer Application on Celery (*Apium graveolens* L.) Production and Soil Improvement

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Abstract: Straw mulching on wet beds is an effective method to alleviate continuous cropping obstacles in greenhouses. However, this technique cannot be applied in the production of leafy vegetables with high planting density. Straw mulching in furrows is an alternative method in this circumstance. In this study, celery (*Apium graveolens* L.), a vegetable that prefers a high planting density and wet soil, was used to test furrow straw mulching technology, and the effect of different straw amounts and straw decomposers on soil improvement and celery production was investigated. The results showed that straw mulching in furrows significantly reduced soil conductivity and nitrate nitrogen levels, increased the contents of soil organic carbon as well as phosphorus and potassium nutrients in the bed, and improved celery yield and quality, indicating the significant lateral movement of released nutrients between the furrow and bed. The positive effects of 15,000 kg/ha straw application were more pronounced than those of 7500 kg/ha and 11,250 kg/ha. In addition, straw decomposers accelerated nutrient release and improved celery yield and quality. A decomposer named “ZhuBang” containing *Bacillus licheniformis* was the most effective. We concluded that furrow straw mulching combined with straw decomposer application is an effective measure for the sustainable production of leafy vegetables in intensive vegetable production facilities.

Keywords: straw mulching; furrow; straw decomposer; celery; yield; soil improvement



Citation: Zheng, Z.; Zhou, W.; Yang, Q.; Jiang, J.; Miao, M. Effect of Furrow Straw Mulching and Straw Decomposer Application on Celery (*Apium graveolens* L.) Production and Soil Improvement. *Agronomy* **2023**, *13*, 2774. <https://doi.org/10.3390/agronomy13112774>

Academic Editors: Othmane Merah, Purushothaman Chirakkuzhyil, Abhilash, Magdi T. Abdelhamid, Hailin Zhang and Bachar Zebib

Received: 10 October 2023

Revised: 29 October 2023

Accepted: 2 November 2023

Published: 6 November 2023



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1. Introduction

Vegetable production in facilities is an important part of China’s agriculture. According to announcements by the Chinese government and relevant departments, the area of modern facility cultivation in China has reached 2.67 million ha, and the area of facility agriculture accounts for more than 80% of the total area in the world, of which facility vegetable cultivation accounts for 81% of the area of facility cultivation in China. (https://www.gov.cn/yaowen/liebiao/202308/content_6897358.htm, accessed on 1 September 2023; https://www.moa.gov.cn/ztl/2023yhwj/xcbd_29328/202303/t20230309_6422688.htm, accessed on 1 September 2023; https://www.moa.gov.cn/ztl/ymksn/gmrbbd/202205/t20220526_6400512.htm, accessed on 17 October 2023). A survey of relevant government departments shows that, in 2021, China’s facility vegetable production reached 230 million tons, accounting for 30% of the total vegetable production (https://www.gov.cn/zhengce/202307/content_6890148.htm, accessed on 17 October 2023). By artificially regulating various environmental factors in the process of facility vegetable cultivation, the production cycle of vegetables can be shortened, vegetable yields

can be increased, and the economic benefits of growers can be improved [1]. However, farmers often apply excessive fertilizers in pursuit of higher economic returns from facility vegetable cultivation, which not only results in a large amount of waste and residue of fertilizers with the extension of planting years but also leads to widespread and serious succession barriers such as soil salinization, acidification, serious nitrate accumulation, and soil nutrient imbalance in facility soils, which eventually lead to a significant decline in the economic and ecological benefits and seriously restrict the sustainable development of the Chinese vegetable industry [2,3]. Therefore, how to effectively improve the physical and chemical properties of soil and alleviate the obstacles of successive cropping is an important issue that needs to be addressed urgently.

Straw is a renewable resource containing rich nutritional elements and can be directly utilized. The main types of straw include wheat straw, rice straw, and corn straw. China produces 1 billion tons of straw annually, about 30% of the world's total straw production [4]. According to the statistics of relevant departments of the Chinese government, the comprehensive utilization rate of straw in China was 88.1% in 2021, including returning straw to fields and using it as feed and as a substrate for edible fungi cultivation [5,6]. Returning straw to fields is a typical agricultural practice and serves as the primary approach for consuming straw resources [7]. The technique not only enhances straw utilization efficacy but also substantially reduces the burning and wastage of crop straws, thereby ameliorating agricultural production and the domestic environment in rural areas. Nutrients in the straw that are gradually released as the straw decomposes have an important impact on crop yield improvement [8]. In addition, straw is beneficial to improving physical and chemical properties of the soil; straw mulch on the surface effectively reduces wind and rain erosion and soil water loss, and decomposed straw can increase the soil organic matter, soil porosity, and soil aeration and reduce the soil volumetric weight and soil nitrogen concentration, effectively alleviating soil crop succession barriers [9,10]. However, an excessive amount of straw returned to a field can bring a series of issues: (1) it lengthens the straw decomposition duration, which leads to inadequate nutrient release; (2) straw decomposition competes with crops for nitrogen sources, which inhibits crop growth and reduces yield; (3) there will still be a large amount of straw not fully decomposed after a crop harvest, which affects the growth of the next crop [11,12]. Therefore, it is necessary to investigate the most suitable amount of straw to be returned to the field in vegetable cultivation and to find ways to improve the straw decomposition rate.

The main components of straw decomposers are *Bacillus*, *Actinomyces*, yeast, and other microorganisms that are beneficial for decomposing cellulose in the straw [13–15]. Compared with physical and chemical treatments, fermentation and the enzymatic decomposition of straw by microorganisms do not produce secondary pollution, require low energy consumption, and are more safe, environmentally friendly, and economical [16,17]. Straw-decomposing bacteria are widely used in straw return, which can accelerate the degradation rate of crop straw and improve the utilization efficiency of straw [18]. Moreover, previous studies have found that straw-decomposing bacteria can not only increase the number of straw-degrading microorganisms in the soil but also stabilize and increase the nutrient content [19]. Currently, these microorganisms are commonly used in field crops such as rice, wheat, and corn [20,21]. However, a large number of vegetables are produced in facilities (such as plastic sheds). Due to the well-insulated performance of sheds, temperatures inside them are often higher than outside, and this temperature difference is more pronounced during daylight hours [22]. In addition, the amount of irrigation inside a shed is usually much higher than outside, and the annual irrigation often exceeds 1300 mm, which leads to high-temperature and high-humidity climatic conditions inside the shed [23]. The activity of straw-decomposing bacteria is easily affected by the environment. However, there are few studies on whether the application of straw decomposers can effectively decompose straw under high temperature and high humidity facility conditions.

Paddy–upland rotation is an effective method to alleviate continuous cropping obstacles [24]. However, growing paddy crops in vegetable facilities is time-consuming and

laborious, which greatly limits the application of this technology. In recent years, we have developed a technique called “wet-upland rotation”, which replaces flooded cultivation with humid cultivation (soil relative humidity 90~100%) [25]. Compared with paddy-upland rotation, our previous works have shown that “wet-upland rotation” has similar positive effects on vegetable growth and soil properties but lower costs, which is more practical and easier for growers to accept. Since the humid environment facilitates straw decomposition and nutrient release [26], the straw mulching on the beds of the wet crop in the wet-upland rotation has a more significant effect on alleviating continuous cropping obstacles [25]. Many leafy vegetables can grow well under high soil humidity environments and are suitable for wet-upland rotation. However, the high planting density of most leafy vegetables impedes the application of straw mulching on beds. Straw mulching in the furrows may be an alternative method in the wet-upland rotation system using leafy vegetables as the wet crop.

Celery (*Apium graveolens* L.) is a common leafy vegetable widely cultured in the world [27]. Celery production has a high demand for fertilizer. Navarro et al. found that the highest celery yield (12.54 kg/m²) was achieved when N, P, and K were applied at 257 kg/ha, 38 kg/ha, and 475 kg/ha, respectively [28]. In southern China, celery can be cultivated all year round, but it grows best at temperatures between 15 °C and 20 °C [29]. Celery also has a high water demand during growth and can be used for wet-upland rotation [30,31]. Therefore, celery was used as the cultivated crop to explore the effects of different straw amounts and different straw decomposers on the soil physicochemical properties and the celery yield and quality. We investigated whether furrow straw mulching technology and straw decomposer application were feasible under intensive leafy vegetable production facilities.

2. Materials and Methods

2.1. Study Site and Climate

The experiment was conducted at the experimental farm of Yangzhou University in Hanjiang District, Yangzhou City, Jiangsu Province, China (32°38' N, 119°4' E) from March to July and July to November 2021. The study site is characterized by a subtropical monsoon climate with an average temperature of 17 °C and an average precipitation of 1063.2 mm in 2021 (<https://www.huaon.com/channel/distdata/904855.html>, accessed on 25 October 2023). The air and soil temperature (10 cm depth) (Figures S1 and S2) and the photosynthetically active radiation (Figure S3) at 12:00 h were recorded daily by an agrometeorological station (TH-WPQX, Shandong Tianhe Environmental Science and Technology Co., Ltd., Weifang, China) during our experimental period. The characteristics of the soil types in the studied area are shown in Table S1. To facilitate the comparison of changes in the soil properties before and after celery planting, some soil properties before celery planting are included in the figures in the Section 3.

2.2. Experimental Materials

The variety of celery (*Apium graveolens* L.) used was “Jinnan 1” (Tianjin Xingke Seed Co., Ltd., Tianjin, China). The straw used in this experiment included rice and wheat straw; the wheat variety was “Zhengmai 1860” (Henan Feike Seed Industry Co., Ltd., Xinxiang, China), and the rice variety was “Nanjing 518” (Jiangsu Ruihua Agricultural Science and Technology Co., Ltd., Suqian, China). The straw was machine-cut to a length of about 10 cm. The nutrient composition of both types of straw is shown in Table S2.

2.3. Experimental Design and Treatments

According to the harvesting period of rice and wheat, rice straw was used in the March–July experiment and wheat straw was used in the July–November experiment. On 15 March and 15 July, straw was mulched in the furrow, and celery seeds were sown on the beds at a rate of 4.5 kg/ha. A 90% relative soil humidity was kept by sprinkler irrigation after sowing and was confirmed with a soil moisture meter (BYKZ-5, Boyun, Weifang,

China). Each shed was covered with shade netting to maintain the temperature inside the shed during the experiment. Fertilizer solution was spread evenly over the beds. The amount and schedule of the fertilizer application for celery are shown in Table S3.

The experiments were performed in plastic sheds measuring 16 m in length and 5 m in width. Four treatments (plots) were arranged in each shed. The setup of the plots in the sheds is shown in Figure 1. The sheds were partitioned by steel plates buried 40 cm underground to prevent the transverse moving of nutrients between treatments. For the straw mulching experiment (no straw decomposer was added), the four treatments were: S_{15000} with a mulching amount of 15,000 kg/ha (the maximum amount of straw that can be filled in the furrows), S_{11250} with a mulching amount of 11,250 kg/ha, S_{7500} with a mulching amount of 7500 kg/ha, and the control (CK_1 , no straw mulching). For the straw decomposer experiment, we screened three straw decomposers with different compositions and set up four treatments: SD_1 : straw decomposer “JiaLefeng” (Zhongxin Biotechnology Co., Ltd., Cangzhou, China, <http://czzxsw.com>, accessed on 10 March 2022), whose main ingredients were *Bacillus subtilis*, yeast, and *Aspergillus niger*, with an effective viable count of $\geq 5 \times 10^7$ CFU/g; SD_2 : straw decomposer “LanYue” (LanYue Technology Co., Ltd., Chengdu, China, <http://www.lanyuetech.com>, accessed on 10 March 2022), with the main components of *Bacillus subtilis*, *Streptomyces microflavus*, *Aspergillus niger*, and *Trichoderma viride*, with an effective viable bacterial count of $\geq 5 \times 10^7$ CFU/g; SD_3 : straw decomposer “ZhuBang” (Huahong Biotechnology Co., Ltd., Chengdu, China, <http://www.cdhuahong.com>, accessed on 10 March 2022), with the main components of *Bacillus subtilis*, *Bacillus licheniformis*, yeasts, and *Trichoderma viride*, and an effective viable bacterial count of $\geq 5 \times 10^7$ CFU/g; and no application of straw decomposer as the control (CK_2). The amount of straw mulched in the furrows was 15,000 kg/ha in the straw decomposer experiment. The dosage of the straw decomposer was 2 kg per 1000 kg of straw, which was evenly sprinkled on the surface of the straw with the irrigation water to make the straw moist. Both experiments were conducted with a randomized block design with four replications, and in total, eight sheds were used in this study.

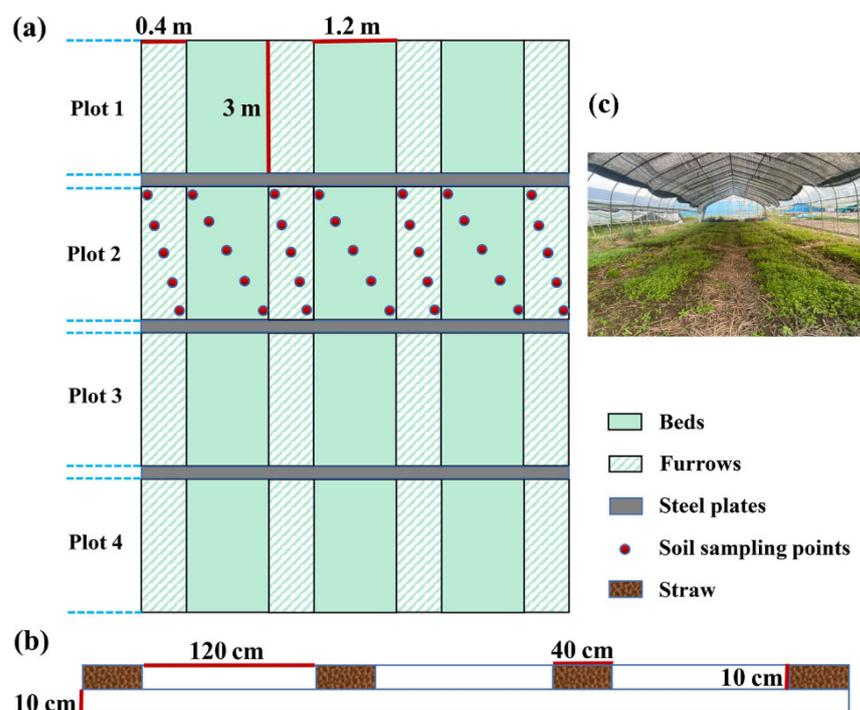


Figure 1. Schematic of the experimental design and schematic of the longitudinal section of the 0–20 cm soil layer of the shed and the actual view of the experimental shed. (a) Schematic diagram of

a shed. Green represents the beds, stripes represent the furrows, gray represents the steel plates separating the plots. Soil sampling was performed in each furrow and bed; red dots represent the locations of the furrow and bed sampling points; red lines represent the length and width of the beds and furrows. The experiments were conducted in a randomized block design. Plot 1, Plot 2, Plot 3, and Plot 4 in the figure represent plots with different treatments. (b) Schematic diagram of the longitudinal section of the 0~20 cm soil layer in the shed. The depth of the furrows is 10 cm and the brown color represents the straw mulched in the furrows. Red lines represent the width of the beds and furrows and the depth of the soil layer. (c) Actual view of the experimental shed. The beds were planted with celery, the furrows were mulched with straw, and the steel plates were buried 40 cm underground.

Referring to Li [32] and Schleuss et al. [33], soil sampling was conducted using the diagonal method, with 5 sampling points in each furrow and bed. Each plot was sampled in all 4 furrows and 3 beds, and at the end of the sampling, the soil samples were mixed homogeneously at 0~10 cm in the furrows and 0~10 cm and 10~20 cm in the beds, respectively.

2.4. Straw Decomposition Rate

The straw decomposition rate was determined according to the method of Zhu et al. [26]. The collected straw was put into an oven to dry before determination. The straw decomposition rate was measured on 10 July (for 15 March mulch) and 10 November (for 15 July mulch). The calculation formula is as follows:

$$\text{Straw decomposition rate} = (M_{\text{before straw mulching}} - M_{\text{before celery harvest}}) / M_{\text{before straw mulching}}$$

where M indicates the dry weight of straw.

2.5. Yield and Quality Analysis

Celery was harvested using a sickle at 2 to 3 cm above the ground and weighed for each plot. The total nitrogen of celery was determined via the Kjeldahl method [34]. The total phosphorus was determined spectrophotometrically [35]. The total potassium was determined via flame atomic absorption spectrophotometry [36]. The dietary fiber was determined via the method of Wang et al. [37]. The vitamin C content was determined using the anthrone colorimetric method [38]. The total flavonoids were determined using high-performance liquid chromatography, and the total phenols were determined via the UV spectrophotometric method [39].

2.6. Soil Analysis

Soil and water were mixed at a mass ratio of 1:1, and soil conductivity was determined after shaking for 1 h [40]. Soil total organic carbon content was determined via the potassium dichromate oxidation method [41], soil nitrate nitrogen content was determined via UV absorption spectrometry [42], soil total phosphorus content was determined via the perchloric acid ablation method [42], and soil total potassium content was determined via flame photometry [43]. The available phosphorus was determined via the sodium bicarbonate method, and the available potassium was determined using atomic absorption spectrophotometry [44,45].

2.7. Statistical Analysis

The data are presented as the means and standard deviations of three observations. The data were organized and analyzed using Microsoft Excel 2021 and SPSS 25.0 (IBM, Armonk, NY, USA), respectively. Analysis of variance (ANOVA) was performed using SPSS 25.0 (IBM, Armonk, NY, USA). Tukey's *t*-test was used to assess the significant differences at the 5% level.

3. Results

3.1. Different Straw Mulch Amounts

3.1.1. Straw Decomposition Rate

As shown in Figure S4, the decomposition rate of wheat straw was higher than that of rice straw. When the straw mulch amount was 7500 kg/ha, the decomposition rate was the highest, which was 82.53% (rice straw) and 91.38% (wheat straw), respectively. With an increase in the straw amount, the decomposition rate gradually decreased, but after 4 months of decomposition, the S₁₅₀₀₀ treatment (rice straw mulching), which had the lowest decomposition rate, also had a decomposition rate of 64.8%.

3.1.2. Changes in the Properties of Soil Layers in the Furrows at 0~10 cm

Since the straw covered the furrows, we determined the soil physicochemical properties at 0~10 cm in the furrows. Wheat straw mulching improved organic carbon (S₁₁₂₅₀ and S₁₅₀₀₀ treatments), total phosphorus, available phosphorus, and available potassium (S₇₅₀₀ and S₁₁₂₅₀ treatments) more than rice straw mulching (Table S4). Straw mulching significantly reduced the soil conductivity by 29.49% to 50.43% and the nitrate nitrogen content by 34.01% to 56.14%, while it remarkably increased the soil organic carbon (Figure 2a,b,d). Compared with CK₁, straw mulching significantly increased the total and available phosphorus contents by 1.00% to 2.87%, and the total and available potassium content by 6.64% to 18.54% (Figure 2e–h). Generally, the more straw that was mulched, the greater the decrease in the soil conductivity and the nitrate nitrogen content, and the greater the observed increase in the organic carbon, total nitrogen, phosphorus, and potassium nutrient contents.

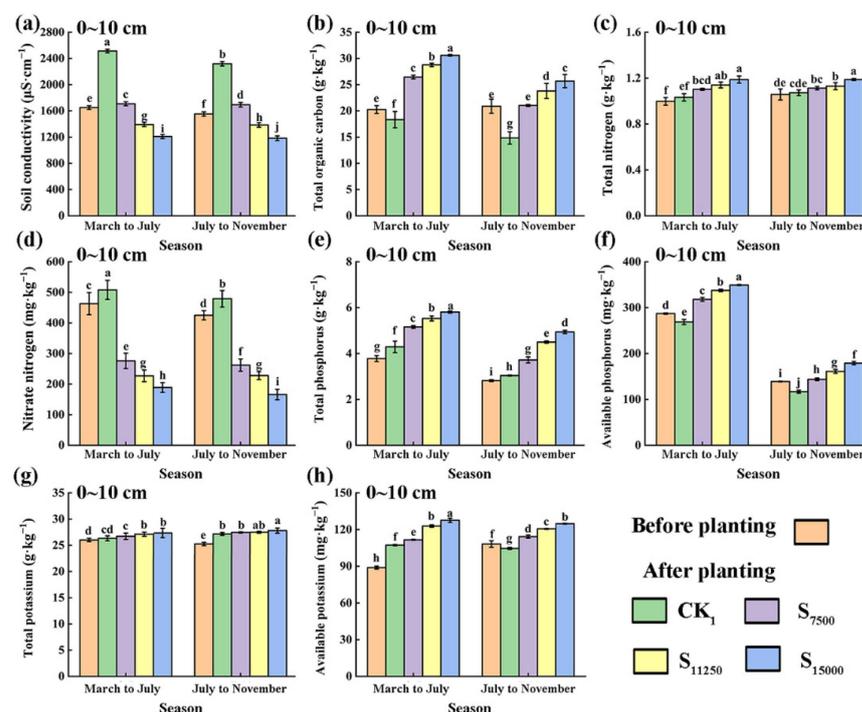


Figure 2. Changes in the soil conductivity, total organic carbon, total nitrogen, nitrate nitrogen, total phosphorus, available phosphorus, total potassium, and available potassium in the 0~10 cm soil layer of furrows after different amounts of straw mulching. (a) Soil conductivity. (b) Total organic carbon. (c) Total nitrogen. (d) Nitrate nitrogen. (e) Total phosphorus. (f) Available phosphorus. (g) Total potassium. (h) Available potassium. CK₁: no mulching straw, S₇₅₀₀: mulching straw amount 7500 kg/ha, S₁₁₂₅₀: mulching straw amount 11,250 kg/ha, S₁₅₀₀₀: mulching straw amount 15,000 kg/ha. Different lowercase letters above bars indicate significant differences between different treatments based on bidirectional ANOVA tests (p < 0.05). Rice straw was used in March–July; wheat straw was used in July–November.

3.1.3. Changes in the Properties of Soil Layers in the Beds at 0~10 cm and 10~20 cm

To investigate whether the straw mulched in the furrows affected the soil properties in the bed, the physicochemical properties of the soil in the beds were measured at 0 to 10 cm and 10 to 20 cm. The results showed that compared with the rice straw mulching, the wheat straw mulching was more effective in improving the conductivity, total nitrogen, nitrate nitrogen, total phosphorus, and total potassium in the 0~10 cm layer of soil and the nitrate nitrogen in the 10~20 cm layer of soil (Table S4). The soil conductivity at 0~10 cm in the beds was significantly higher than that at 10~20 cm. Compared with the pre-planting stage, the soil conductivity was significantly increased by 68.51% (0~10 cm) and 34.96% (10~20 cm) after planting in CK₁. Compared with CK₁, the straw mulching significantly increased the organic carbon content at 0~10 cm in the beds, and different amounts of straw mulching had no significant effect on the organic carbon content at 10~20 cm in the beds (Figure 3b,j). The nitrate nitrogen content of soil in CK₁ was increased by 15.19% (0~10 cm) and 19.11% (10~20 cm) after planting compared with that before planting. Straw mulching significantly reduced the nitrate nitrogen content at both 0~10 cm and 10~20 cm in the beds (Figure 3d,l). The phosphorus and potassium nutrient contents at 0~10 cm decreased significantly, and the phosphorus and potassium nutrient contents at 10~20 cm decreased significantly, except for the total phosphorus compared with the pre-planting stage. Straw mulching significantly increased the soil total and available phosphorus and total and available potassium, and the higher the amount of straw mulching, the higher the soil phosphorus and potassium nutrient enhancement (Figure 3c,e-h,k,m-p).

3.1.4. Yield and Quality of Celery

As can be seen from Figure 4a, straw mulching significantly increased the celery yield, and the S₁₅₀₀₀ treatment had the best celery yield. At the same amount of straw mulching, the celery yield was significantly higher in the rice straw mulching than in the wheat straw mulching. The increase in celery yield ranged from 6.08% to 12.18% after rice straw mulching and from 7.53% to 11.71% after wheat straw mulching. Straw mulching also had an influence on the nitrogen, phosphorus, and potassium contents of celery. At the same amount of straw mulching, the total nitrogen content of celery in the wheat straw mulching was lower than that in rice straw mulching, and the S₇₅₀₀ treatment had the lowest total nitrogen content of celery (Figure 4b). The total phosphorus content of celery was at its maximum in the S₁₁₂₅₀ treatment (rice straw mulching) and the S₁₅₀₀₀ treatment (wheat straw mulching), respectively (Figure 4c). Both rice and wheat straw mulching significantly increased the total potassium content of celery. The S₁₁₂₅₀ treatment significantly increased the total potassium content of celery, and there was no significant difference in the total potassium content of celery with a further increase in the amount of mulching (Figure 4d).

We also measured the main functional components of celery. The results showed that compared with the rice straw mulching, the wheat straw mulching was more effective in improving the dietary fiber, Vc (Vitamin C), flavonoids, and total phenolic contents of celery (Table S4). The dietary fiber and Vc content of the celery mulched with rice straw was significantly lower than that of the celery mulched with wheat straw at the same amount of straw mulching (Figure 4e,f). The total flavonoids and total phenolic contents of celery were highest in the S₁₁₂₅₀ treatment and significantly decreased in the S₁₅₀₀₀ treatment after mulching with rice straw. In contrast, the total flavonoids and total phenolic contents of celery continued to increase under the wheat straw mulching and reached a maximum in the S₁₅₀₀₀ treatment (Figure 4g,h).

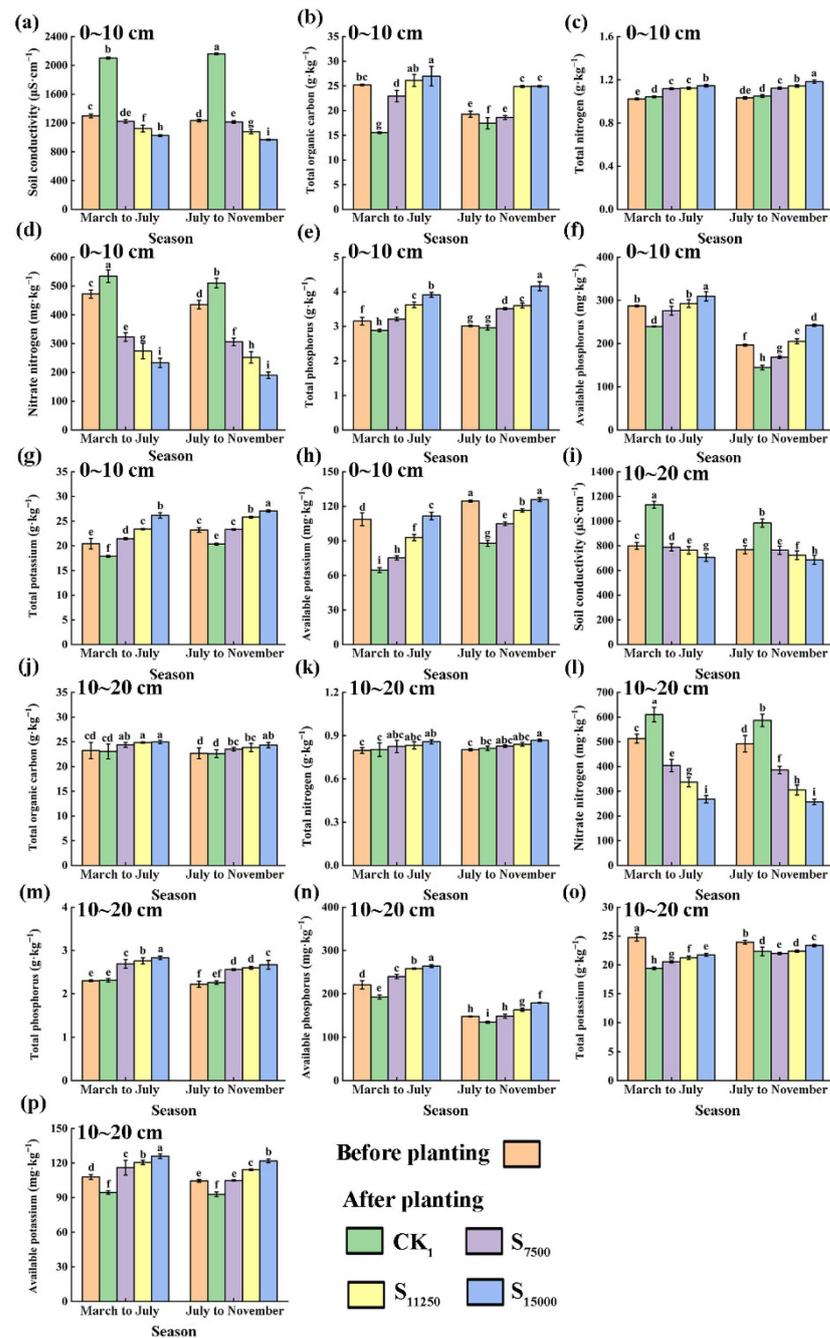


Figure 3. Changes in the soil conductivity, total organic carbon, total nitrogen, nitrate nitrogen, total phosphorus, available phosphorus, total potassium, and available potassium in the 0~10 cm and 10~20 cm soil layers of beds after different amounts of straw mulching. (a) Soil conductivity at 0~10 cm. (b) Total organic carbon at 0~10 cm. (c) Total nitrogen at 0~10 cm. (d) Soil nitrate nitrogen at 0~10 cm. (e) Total phosphorus at 0~10 cm. (f) Available phosphorus at 0~10 cm. (g) Total potassium at 0~10 cm. (h) Available potassium at 0~10 cm. (i) Soil conductivity at 10~20 cm. (j) Total organic carbon at 10~20 cm. (k) Total nitrogen at 10~20 cm. (l) Nitrate nitrogen at 10~20 cm. (m) Total phosphorus at 10~20 cm. (n) Available phosphorus at 10~20 cm. (o) Total potassium at 10~20 cm. (p) Available potassium at 10~20 cm. CK₁: no mulching straw, S₇₅₀₀: mulching straw amount 7500 kg/ha, S₁₁₂₅₀: mulching straw amount 11,250 kg/ha, S₁₅₀₀₀: mulching straw amount 15,000 kg/ha. Different lowercase letters above bars indicate significant differences between different treatments based on bidirectional ANOVA tests ($p < 0.05$). Rice straw was used in March–July; wheat straw was used in July–November.

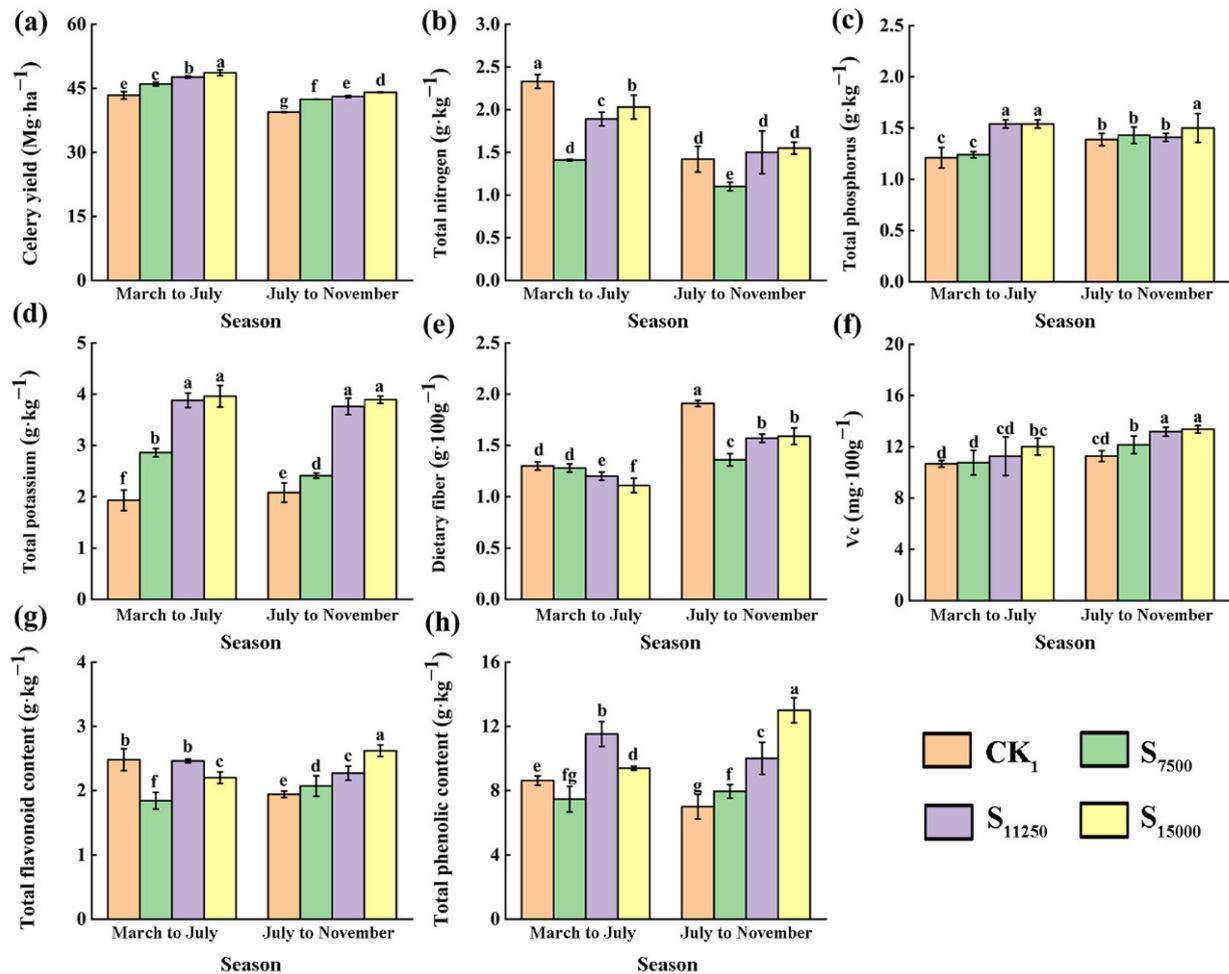


Figure 4. Changes in celery yield and quality under different crop straw mulching experiments. (a) Celery yield. (b) Total nitrogen. (c) Total phosphorus. (d) Total potassium. (e) Dietary fiber. (f) Vitamin C. (g) Total flavonoid content. (h) Total phenolic content. CK₁: no mulching straw, S₇₅₀₀: mulching straw amount 7500 kg/ha, S₁₁₂₅₀: mulching straw amount 11,250 kg/ha, S₁₅₀₀₀: mulching straw amount 15,000 kg/ha. Different lowercase letters above bars indicate significant differences between different treatments based on bidirectional ANOVA tests ($p < 0.05$). Rice straw was used in March–July; wheat straw was used in July–November.

3.2. Different Types of Straw Decomposer Application Experiment

3.2.1. Straw Decomposition Rate

As can be seen from Figure S5, the application of straw decomposers significantly increased the rate of straw decomposition. The decomposition rate of the wheat straw experiment was higher than that of the rice straw experiment. Compared to CK₂, the application of straw decomposers increased the rice straw decomposition by 23.40% to 32.95% and the wheat straw decomposition by 8.99% to 15.75%. The SD₃ treatment had the highest straw decomposition rate of 86.15% (rice straw mulching) and 95.49% (wheat straw mulching), respectively.

3.2.2. Changes in Properties of the Soil Layer in the Furrows at 0–10 cm

Wheat straw mulching was more effective in ameliorating the soil conductivity, total nitrogen (SD₃ treatment), nitrate nitrogen, total phosphorus, effective phosphorus (SD₃ treatment), total potassium (SD₂ and SD₃ treatments), and effective potassium than rice straw mulching (Table S5). The application of straw decomposers significantly reduced soil conductivity, with the SD₃ treatment showing the greatest reduction of 15.66% (Figure 5a).

The soil organic carbon content at 0~10 cm in the furrows was significantly increased after celery planting. Compared with CK₂, the SD₂ and SD₃ treatments significantly increased the soil organic carbon content (Figure 5b). The soil nitrate nitrogen content decreased significantly in CK₂ after planting compared with that before celery planting. The application of straw decomposers significantly reduced the soil nitrate nitrogen content, and the SD₃ treatment had the greatest effect on soil nitrate nitrogen at 25.46% (Figure 5d). Compared with CK₂, the total and available phosphorus contents were significantly increased in the SD₃ treatment (Figure 5e,f). Compared with CK₂, the SD₃ treatment showed the greatest elevation in the soil total potassium and available potassium content, with a 6.45% increase in the soil total potassium content and a 19.29% increase in the soil available potassium content (Figure 5g,h).

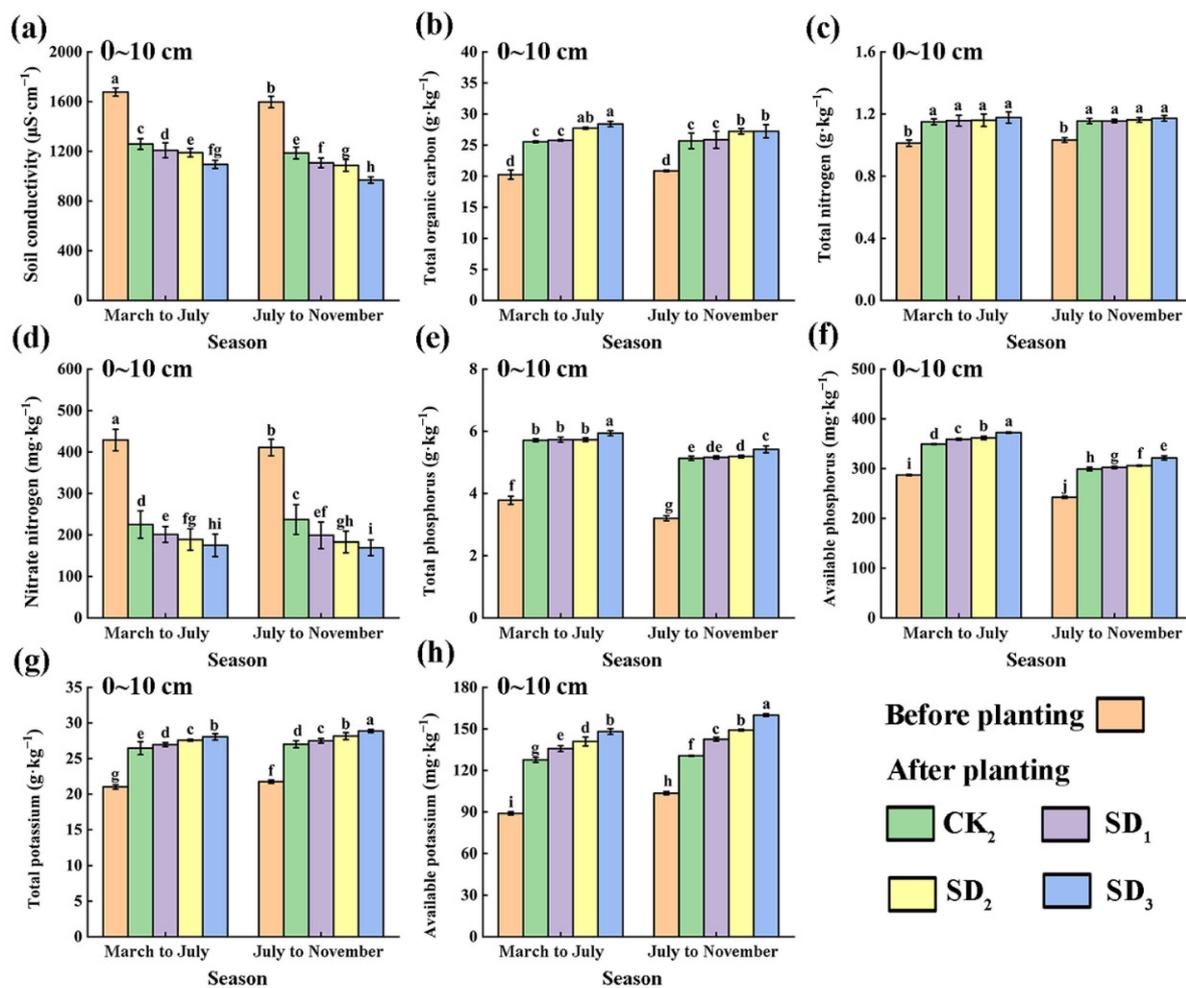


Figure 5. Changes in the soil conductivity, total organic carbon, total nitrogen, nitrate nitrogen, total phosphorus, available phosphorus, total potassium, and available potassium in the 0~10 cm soil layer of furrows after different types of straw decomposer application. (a) Conductivity. (b) Total organic carbon. (c) Total nitrogen. (d) Nitrate nitrogen. (e) Total phosphorus. (f) Available phosphorus. (g) Total potassium. (h) Available potassium. CK₂: no straw decomposer added. SD₁: straw decomposer "JiaLefeng", SD₂: straw decomposer "LanYue", SD₃: straw decomposer "ZhuBang". Different lowercase letters above bars indicate significant differences between different treatments based on bidirectional ANOVA tests ($p < 0.05$). Rice straw was used in March–July; wheat straw was used in July–November.

3.2.3. Changes in the Properties of Soil Layers in Beds at 0~10 cm and 10~20 cm

Compared with rice straw mulching, wheat straw mulching was more effective in ameliorating soil conductivity (SD₁ and SD₂ treatments), organic carbon (SD₂ and SD₃ treatments), total nitrogen (SD₂ treatment), total phosphorus (SD₁ treatment), available phosphorus, total potassium (SD₃ treatment), and available potassium (SD₁ treatment) in the 0~10 cm layer of soil and the total nitrogen (SD₂ treatment), nitrate nitrogen, total phosphorus (SD₁ treatment), available phosphorus, and total potassium in the 10~20 cm layer of soil (Table S5). Compared with the pre-planting stage, the conductivity in the 0~10 cm and 10~20 cm layers of the beds decreased significantly in all treatments after planting. All three straw decomposition treatments significantly reduced the soil conductivity compared to the CK₂, but the SD₃ treatment had the most significant effect (Figure 6a,i). The soil organic carbon content increased significantly in all treatments after planting. Compared with CK₂, the SD₃ treatment significantly increased the organic carbon content of soil after celery planting (Figure 6b,j). Compared with the pre-planting stage, the soil nitrate nitrogen content decreased significantly after planting. Compared with CK₂, the straw decomposer treatment significantly reduced the soil nitrate nitrogen content by 10.03% to 24.93% (0~10 cm) and 11.83% to 12.44% (10~20 cm) (Figure 6d,l). Compared with CK₂, the total nitrogen and total phosphorus and available phosphorus contents in the 0~10 cm of the beds were significantly higher in the SD₃ treatment. Application of straw decomposers did not significantly increase the total nitrogen and total phosphorus and available phosphorus contents in the 10~20 cm of the beds (Figure 6c,e,f,k,m,n). Compared with CK₂, the SD₂ and SD₃ treatments had significantly higher levels of total potassium and available potassium in the 0~10 cm of the beds, and the SD₁, SD₂, and SD₃ treatments had significantly higher levels of available potassium in the 10~20 cm of the beds (Figure 6g,h,o,p).

3.2.4. Yield and Quality of Celery

Wheat straw mulching improved the yield, total nitrogen, total phosphorus, and total potassium (SD₂ and SD₃ treatments) of celery better than rice straw mulching (Table S5). The SD₃ treatment showed the highest increase in celery yield compared with CK₂ (Figure 7a). Compared with CK₂, mulching with rice straw significantly increased the total nitrogen content of celery in the SD₃ treatment, and mulching with wheat straw significantly increased the total nitrogen content of celery in the SD₂ and SD₃ treatments (Figure 7b). Compared with CK₂, the total phosphorus content of celery was significantly higher in the SD₁ and SD₃ treatments after mulching with rice straw and in the SD₂ and SD₃ treatments after mulching with wheat straw (Figure 7c). The total potassium content of celery was significantly higher after rice straw mulching than after wheat straw mulching. Compared with CK₂, mulching with rice straw significantly increased the total potassium content of the SD₂ and SD₃ treatments (Figure 7d).

We measured the effects of different types of straw decomposer applications on the functional composition of celery. The study showed that compared with rice straw mulching, wheat straw mulching was more effective in ameliorating Vc (SD₂ treatment) and total phenolics (SD₂ treatment) in celery (Table S5). The dietary fiber content of celery was significantly decreased in both the SD₂ and SD₃ treatments, regardless of straw type, whereas it was significantly decreased in the SD₁ treatment only under mulching with wheat straw (Figure 7e). After straw mulching, there was no significant difference in Vc content between the SD₁ treatment and CK₂. The SD₂ treatment and SD₃ treatment had significantly higher Vc contents than CK₂ (Figure 7f). After the application of straw decomposer, the total flavonoid content of celery under the SD₂ treatment and SD₃ treatment was significantly increased over that of CK₂ (Figure 7g). Both rice straw and wheat straw mulching significantly increased the total phenolic content of celery in the SD₃ treatment (Figure 7h). The study showed that the best quality of celery was obtained from the SD₃ treatment.

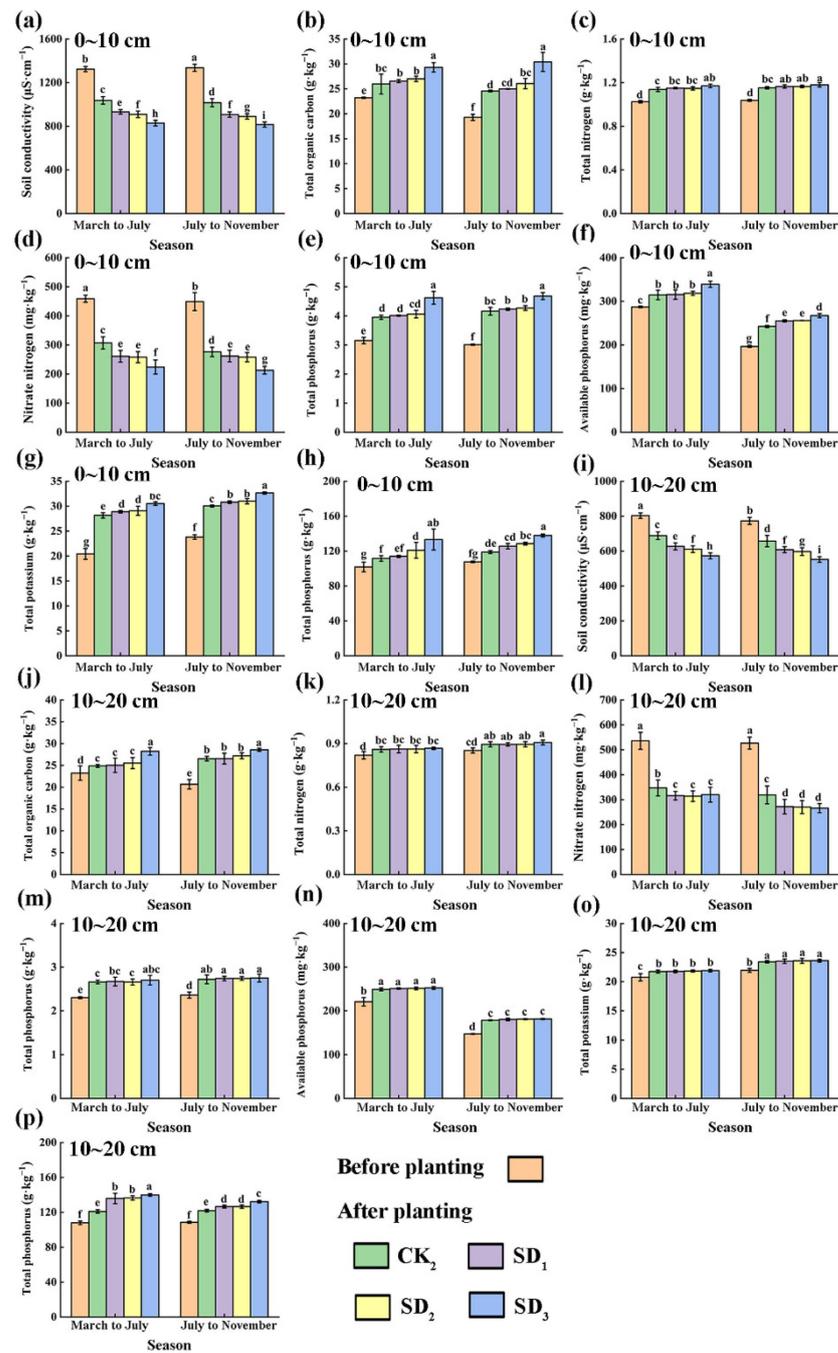


Figure 6. Changes in the soil conductivity, total organic carbon, total nitrogen, nitrate nitrogen, total phosphorus, available phosphorus, total potassium, and available potassium in the 0~10 cm layer and the 10~20 cm layer of beds after different types of straw decomposer application. (a) Soil conductivity at 0~10 cm. (b) Total organic carbon at 0~10 cm. (c) Total nitrogen at 0~10 cm. (d) Nitrate nitrogen at 0~10 cm. (e) Total phosphorus at 0~10 cm. (f) Available phosphorus at 0~10 cm. (g) Total potassium at 0~10 cm. (h) Available potassium at 0~10 cm. (i) Soil conductivity at 10~20 cm. (j) Total organic carbon at 10~20 cm. (k) Total nitrogen at 10~20 cm. (l) Nitrate nitrogen at 10~20 cm. (m) Total phosphorus at 10~20 cm. (n) Available phosphorus at 10~20. (o) Total potassium at 10~20 cm. (p) Available potassium at 10~20 cm. CK₂: no straw decomposer added. SD₁: straw decomposer “JiaLefeng”, SD₂: straw decomposer “LanYue”, SD₃: straw decomposer “ZhuBang”. Different lowercase letters above bars indicate significant differences between different treatments based on bidirectional ANOVA tests ($p < 0.05$). Rice straw was used in March–July; wheat straw was used in July–November.

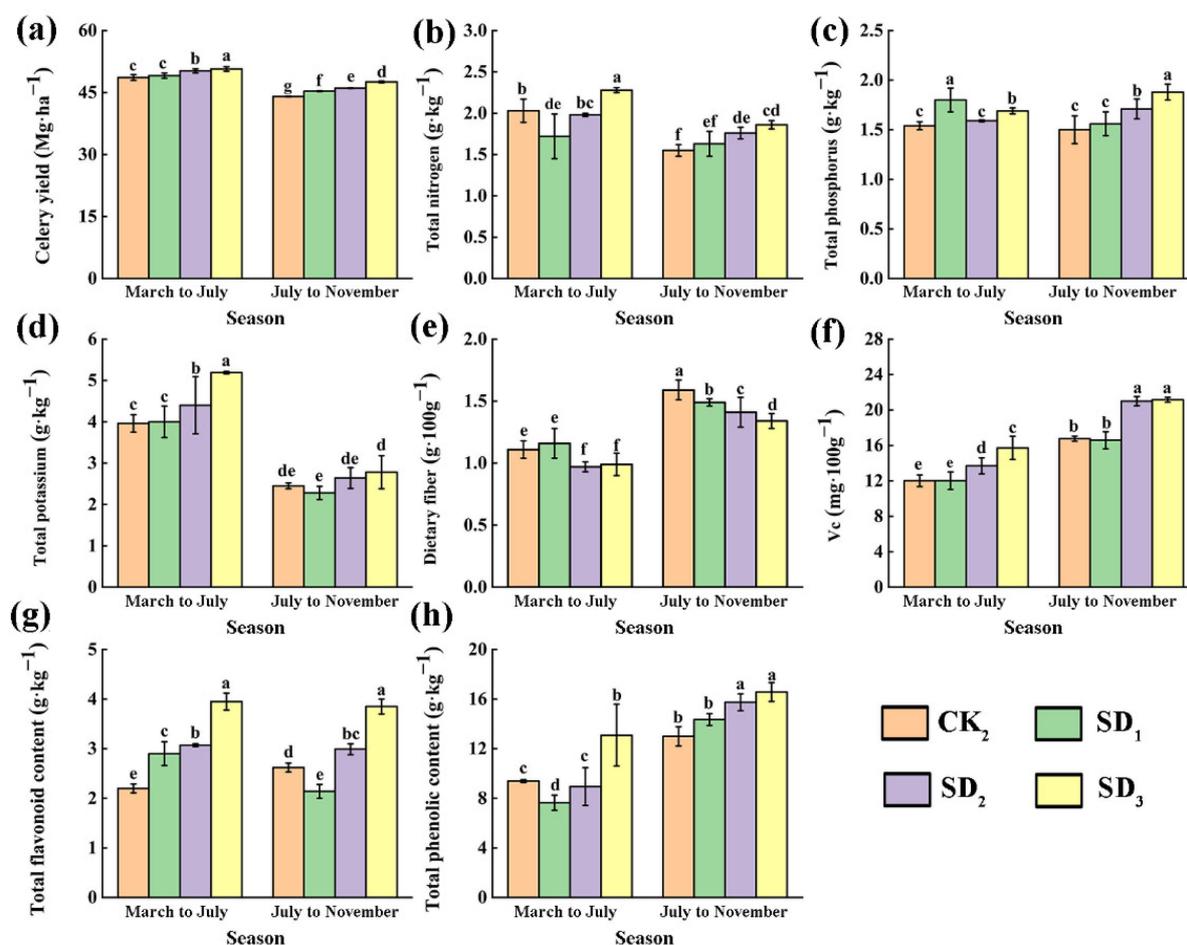


Figure 7. Changes in the celery yield and quality under different types of straw decomposer application. (a) Celery yield. (b) Total nitrogen. (c) Total phosphorus. (d) Total potassium. (e) Dietary fiber. (f) Vitamin C. (g) Total flavonoid content. (h) Total phenolic content. CK₂: no straw decomposer added. SD₁: straw decomposer “JiaLefeng”, SD₂: straw decomposer “LanYue”, SD₃: straw decomposer “ZhuBang”. Different lowercase letters above bars indicate significant differences between different treatments based on bidirectional ANOVA tests ($p < 0.05$). Rice straw was used in March–July; wheat straw was used in July–November.

4. Discussion

To date, straw return to the field is the most widely applied method of straw utilization in the world [46]. Although straw mulching on vegetable beds is a common practice in China and other developing countries, the effect of this technology on vegetable yield and quality and the properties of the soil is less investigated, especially in facilities in which the environment is quite different from open fields. As mentioned above, for some leafy vegetables with high planting density, straw has to be mulched in furrows [4], and this technology has also not been well studied. In this study, positive effects of furrow straw mulching on celery yield and quality and the whole soil properties were found, indicating that furrow straw mulching technology is a powerful tool for sustainable production in intensive leafy vegetable cultivation systems.

The beneficial effects of straw mulching on soil improvement have been well established, including that it alleviates soil salinization, reduces nitrate nitrogen leaching, and increases soil organic carbon content [47–50]. Moreover, straw mulching can improve crop qualities such as Vc, flavonoids, and total phenolics by increasing the soil phosphorus and potassium nutrients [51]. Potassium fertilization can regulate the stomatal opening and improve photosynthesis in plants, thereby increasing the activity of GalLDH,

a key enzyme that catalyzes Vc synthesis, thus leading to an increase in Vc synthesis in plants [52,53]. Also, it has been shown that high potassium fertilizer application increases the production of TNC (D-glucose), a precursor substance for Vc biosynthesis in plants, which leads to the production of more Vc in the L-galactose pathways [54,55]. Some studies have indicated that increasing potassium supply also increases the activity of phenylalanine–ammonia–lyase (PAL) in plants, which increases their flavonoids and the total phenolic content [55]. Liu et al. found that the proper application of phosphorus fertilizer enhanced the inhibition of hydroxyl radicals, superoxide anion radicals, and DPPH radicals and increased the flavonoid content of plants [56]. In some cases, large amounts of straw mulched on beds or tilled into the soil can compete with the crop for nitrogen during decomposition, thus resulting in reduced crop yields [57]. In our study, sufficient soil available nitrogen compensated for the nitrogen consumption for straw decay; thus, the straw mulching alleviated the secondary salinization and nitrogen leaching and increased the celery yield (Figures 3d,l and 4a).

It is important to note that the straw was mulched in furrows, while a positive effect on plant growth and soil improvement was observed in the beds. Our explanation is the lateral movement of the released nutrients of the decomposed straw from the furrow to the bed. In previous reports, the horizontal movement of soil ions and organic carbon was not rare. Zhang et al. and Nie et al. showed that the horizontal migration of organic carbon was related to soil moisture and crop residues [58,59]. Han et al. found that environmental factors affect the lateral migration of soil total phosphorus [60]. Buxbaux et al. found that the potassium content of unfertilized soils converges to the potassium content of fertilized soils, and that there is a significant lateral migration of potassium in soils [61]. In the case of nitrogen, straw consumed the available nitrogen and reduced the nitrate ion in the furrow, thereby resulting in a concentration gradient, which led to the reversed horizontal migration of available nitrogen from the bed to the furrow (Figures 2d and 3d,l). This movement was critical to alleviate the secondary salinization and nitrogen leaching in the bed. In this study, the width of the bed was 1.2 m; theoretically, nutrients should move at least 0.6 m to affect the whole bed. Therefore, it is important to further investigate the dynamics of the lateral nutrient movement in the soil and optimize the straw amount and bed/furrow size in this vegetable production system.

A straw decomposer is a kind of microbial agent that can accelerate the decomposition of straw, and is usually made of a variety of microorganisms such as *Bacillus*, *Actinomycetes*, yeast, *Trichoderma*, and other microbial composites. The growth and reproduction of microorganisms require suitable environmental conditions. Currently, straw decomposers are mainly applied to open fields, while a large number of vegetables are grown in agricultural facilities such as plastic sheds, which have high temperature and humidity [20,21]. The decomposing efficiency of these straw decomposers in agricultural facilities was not clear. Among the three straw decomposers used in this study, the best performance was achieved by “ZhuBang”, the main components of which are *Bacillus subtilis*, *Bacillus licheniformis*, yeasts, and *Trichoderma viride*. *Bacillus licheniformis* was not included in the other two straw decomposers used herein. Some studies have shown that *Bacillus licheniformis* can produce a highly effective cellulase enzyme that accelerates straw decomposition [62]. Sun et al. [63] found that corn straw fermented by *Bacillus licheniformis* reduced cellulose by 35.42%, hemicellulose by 17.47%, and lignin by 20.19%. Moreover, *Bacillus licheniformis* is extremely adaptable to the environment, remaining active and stable at pH 4.0–10 and high temperatures of 40–90 °C [62]. In contrast, the growth of several other microorganisms in the straw decomposers had stricter temperature requirements; the optimum growth temperatures of *Bacillus subtilis*, yeasts, *Aspergillus niger*, *Streptomyces microflavus*, and *Trichoderma viride* are 30 °C, 32 °C, 30 °C, 30–37 °C, and 25 °C, respectively [64–68]. In facilities with high temperatures (Figures S1 and S2), the activity of these microorganisms may decrease and may not achieve the expected decomposition effect, while *Bacillus licheniformis* could grow and reproduce normally, which may be an important reason for the excellent performance of the straw decomposer “ZhuBang” in our experiment.

In this study, the maximum amount of straw application was 15,000 kg/ha, and we found that the optimal effects of straw mulching were realized at this amount. Thus, we have reason to speculate that more straw application may result in better effects. However, the common furrow depth was about 10 cm for leafy vegetable growth, and the maximum amount of straw that could be mulched in the furrow was 15,000 kg/ha. In subsequent studies, we will try to deepen the furrows to further increase the amount of straw mulching to explore whether it can produce better results and then define the amount of straw mulching that will not have a positive effect in order to detect the optimal range.

5. Conclusions

Straw mulching in furrows significantly reduced conductivity and nitrate nitrogen levels of the soil in the beds and furrows, promoted the accumulation of organic carbon as well as phosphorus and potassium nutrients, and improved the yield and quality of celery. In this study, the best improvement in celery yield, quality, and soil properties was achieved at 15,000 kg/ha of straw mulching in the range of 0 to 15,000 kg/ha. In addition, the application of straw decomposers can significantly increase the rate of straw decomposition, accelerate the release of nutrients from straw to soil, and improve the yield and quality of celery in facility vegetable cultivation. The study indicates that the straw decomposer “ZhuBang”, containing *Bacillus licheniformis*, is the most suitable for application in facility vegetable cultivation. The results of the study indicate that straw mulching in furrows and the application of straw decomposers are reasonable measures for the sustainable development of the leafy vegetable industry.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy13112774/s1>. Table S1. Characteristics of soil types before treatments (0–20 cm soil layer). Table S2. Nutrient contents of dry straw. Table S3. Fertilization amount and schedule for celery. Table S4. The rate of increase in each treatment compared with CK₁ under rice and wheat straw mulching. Table S5. The rate of increase in each treatment compared with CK₂ under rice and wheat straw mulching. Figure S1. Temperature variations during experiments. Figure S2. Changes in the soil temperature in the 0–10 cm soil layer of furrows after different types of straw decomposer application. Figure S3. The photosynthetically active radiation during experiments. Figure S4. Decomposition rate of crop straws. Figure S5. Decomposition rate of crop straws.

Author Contributions: Data curation, Z.Z., Q.Y. and J.J.; Formal analysis, Z.Z.; Funding acquisition, M.M.; Investigation, Z.Z., W.Z., Q.Y. and J.J.; Methodology, M.M.; Project administration, M.M.; Resources, Z.Z.; Supervision, M.M.; Validation, Z.Z. and W.Z.; Writing—original draft, Z.Z. and W.Z.; Writing—review & editing, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the R&D Foundation of Jiangsu Province, China (BE2022425) and Jiangsu Modern Agricultural (Vegetable) Industrial Technology System (JATS[2022]495).

Data Availability Statement: Data are contained within the article or Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

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