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Maize Straw Return and Nitrogen Rate Effects on Potato (*Solanum tuberosum* L.) Performance and Soil Physicochemical Characteristics in Northwest China

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Abstract: The average yield of fresh potato tubers per hectare is relatively low in China, partly due to poor nutrient management. Chronic inorganic N enrichment leads to soil acidification, which deteriorates soil fertility. Straw residues are removed from the field or burnt during land preparation, resulting in nutrient depletion and air pollution. However, these residues can be returned to the soil to improve its fertility. Therefore, a two–year experiment was conducted in an existing field with five years of different inorganic nitrogen (N) rate to determine the effects of straw return and N rate on potato growth, tuber yield, and quality, profit margin, and soil physicochemical properties. The experiment consisted of four N rates: 0 (control, CK), 75 (low N rate, LN), 150 (medium N rate, MN), and 300 (high N rate, HN) kg N ha^{-1} with and without straw (9 t ha^{-1}) return. The results showed that straw with N enrichment improved soil fertility, which increased tuber yield and quality. Compared to the control, MN + straw treatment stimulated economic tuber yield (34.73% and 38.34%), profit margin (55.51% and 63.03%), and protein content (20.04% and 25.46%) in 2018 and 2019, respectively. Nitrogen enrichment after straw return is a sustainable practice for stimulating potato tuber yield, profit margin, and improving soil fertility to promote sustainable agriculture development.

Keywords: crop growth rate; dry matter accumulation; photosynthetically active radiation; profit margin; specific gravity; soil fertility

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1. Introduction

Potato (*Solanum tuberosum* L.) is an important food crop in the world with a production of approximately 371 million tons on about 18 million hectares in 2019 [1]. Potato tubers contain high levels of starch and antioxidants, such as amino acids, essential minerals, polyphenols, and vitamins B3, B6, and C [2]. China, the world's largest potato producer, produced about 92 million tons in 2019, accounting for about 25% of global production [1]. Potato is the most important tuber crop, which is usually grown in the semi–arid region in northwest China, accounting for about 36% of the total potato area [3]. According to a report by the U.S. Department of Agriculture [4], 60% of the total potato production in China is directly consumed as food; 10% is processed into food; 12% is used as seed; 5% is used as feed; and the remaining 13% is storage losses. Compared to other potato producing countries, such as the United States of America and New Zealand, the yield of fresh potato tubers per hectare in China is relatively low. China's average fresh potato tuber yield per hectare in 2019 was 62.84% and 62.44% lower than the average fresh potato tuber yield per hectare in the United States of America and New Zealand, respectively [1], partly due to poor nutrient management [5,6], drought [7,8], and disease and pest infestation [9,10].

Generally, soils in potato-growing areas, especially Northwest China, are low in nitrogen and, as a result, excessive inorganic N fertilizers are used to increase potato yield and tuber quality. China is the largest consumer of nitrogen fertilizer, accounting for about 30% of the total global consumption [11]. However, 52% of the total N fertilizer applied is lost due to volatilization, leaching and surface runoff; only 35% is utilized by crops, while 13% is due to soil residues and calculation errors [12]. Nitrogen losses cause groundwater contamination, eutrophication of surface waters and greenhouse effect [13,14]. Moreover, long–term inorganic N enrichment leads to soil acidification [15–18], which deteriorates soil fertility.

One of the most cost–effective and sustainable ways to improve soil fertility is to add straw residues to the soil [19,20]. Decomposition of straw residues after returning to the soil improves soil physical properties [21–23], biological properties [14,24,25] and chemical properties [20,26,27], which improves soil fertility. These soil properties decrease when straw residues are removed from the field or burnt; thus, decreasing the biological fertility and resilience of the soil, resulting in low crop productivity [28]. In China, about 700 million tons of straw residues are produced annually [29], with an increase of 4% in recent decades [30]. Straw residues contain nutrients such as nitrogen (0.65–1.82%), phosphorus (0.08–0.196%), and potassium (1.02–1.94%) [28]. However, these nutrients are not readily accessible to plants due to microbial immobilization and mineralization processes [19,21,31]. Microbial N immobilization is controlled by straw chemical properties [32,33], nutrient availability [31,32], and soil type [34]. Low quality straw residues have high C:N ratio and lignin content, whereas high quality straw has low C:N ratio and lignin content; high quality straw decomposes faster than the low quality straw [19,31,32]. Maize straw has a high C:N ratio; therefore, it requires inorganic N fertilization to meet microbial N requirements and facilitate decomposition [21]. We therefore hypothesized that returning maize straw to soils with different N concentrations or adding different inorganic N rates after straw return will influence decomposition and mineralization dynamics, which in turn will affect potato growth and yield. Returning straw to the soil has different effects on crop yield depending on the type of crop grown [34]. The effects of straw return on cereal crops such as maize, rice and wheat have been extensively studied [27,35–37]; however, the effects on tuber crops such as potato are elusive. Therefore, this study was to investigate the effects of straw return and different inorganic N rates on potato growth, tuber yield and quality, profit margin, and soil physicochemical properties. The study was guided by the following research questions:

1. How nitrogen enrichment after straw return affects potato growth, tuber yield, and tuber quality;
2. How straw return and N enrichment improve soil physicochemical properties.

By answering these questions, we aim to gain a better understanding of the effects of N enrichment after straw return on potato performance and soil physicochemical properties.

2. Materials and Methods

2.1. Experimental Location and Design

A 17-month experiment was conducted from May 2018 to October 2019 on an existing five-year field trial with different nitrogen enrichment established in 2013 at Xiangquan (35°27′ N, 104°30′ E) in Dingxi, Northwest China. The study area has an annual sunshine duration of 2438 h, an uneven rainfall distribution of 400 mm, an average temperature of 6.9 °C and a frost-free period of 140 days [38]. The soil type at the site is a loess soil with a sandy clay texture. The basic physicochemical properties of the soil before straw return in 2018 are presented in Table 1. The study had four inorganic N (urea) rates, namely: control (CK, 0 kg Nha^{-1}), low N rate, (LN, 75 kg Nha^{-1}), medium N rate (MN, 150 kg Nha^{-1}), and high N rate, (HN, 300 kg Nha^{-1}). The treatments were arranged in a randomized complete block design (RCBD) with four replicates. Each experimental plot was divided into two equal parts and one part was incorporated with maize straw (9 t ha^{-1}) at a depth of 0–20 cm, while the other part received no straw application. Thus, making an eight-treatment experiment, namely: CK, CK + S, LN, LN + S, MN, MN + S, HN, and HN + S. The maize straw was obtained from a local maize field (after harvest) at Xiangquan in Dingxi, Gansu province of China. The chemical properties of the maize straw is showed in Table 2. Maize straw was incorporated into the soil three times, namely (i) during land preparation (April 2018); (ii) after potato harvest (October 2018); and (iii) during land preparation of the second season (April 2019). Each experimental plot received the same amount of phosphorus (225 kg ha^{-1}) and potassium (292.5 kg ha^{-1}).

Table 1. Soil physicochemical properties before straw return in 2018.

Treatment	Bulk Density (g cm^{-3})	Total Nitrogen (g kg^{-1})	Organic Carbon (g kg^{-1})	C:N	pH	Avail P (mg kg^{-1})	Avail K (mg kg^{-1})
CK	1.35	1.26	9.86	7.83	8.14	29.70	116.00
LN	1.35	1.34	9.87	7.37	8.13	29.20	110.00
MN	1.34	1.45	9.98	6.88	8.10	28.30	112.00
HN	1.34	1.47	9.95	6.77	8.08	27.90	111.00

C:N, carbon to nitrogen ratio; pH, soil reaction in water (1:2.5); Avail P, available phosphorus; Avail K, available potassium. CK, no N enrichment; CK + S, no N enrichment with straw; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw.

Table 2. Chemical properties of maize straw in 2018 and 2019.

Year	Organic Carbon (g kg^{-1})	Total Nitrogen (g kg^{-1})	Total Phosphorus (g kg^{-1})	Total Potassium (g kg^{-1})	Lignin (%)	C/N	Lignin/N
2018	423.7	9.1	1.2	18.2	11.1	46.6	1.2
2019	410.1	7.9	1.4	17.8	10.8	51.9	1.4

2.2. Land Preparation and Crop Establishment

The field was ploughed after vegetation clearance and the experimental plots (9 m × 7.2 m) were measured. Six ridges (60 cm wide and 20 cm high) were constructed in each experimental plot and covered with a black film mulch to suppress weed growth, promote root growth and conserve soil moisture. Two certified seeds (Qingshu 9 cultivar) obtained from Dingxi Academy of Agricultural Sciences in Dingxi, Gansu province of China, were sown at a depth of 15 cm per hill and two rows were planted per ridge. There was a spacing of 25 cm between plants and 50 cm between rows, resulting in a plant population of 66,717 per hectare. In the 2018 season, potatoes were planted on May 11 and harvested on October 13, while in the 2019 season, planting and harvesting occurred on May 14 and October 9, respectively. All agronomic practices were carried out according to local conventional management measures.

2.3. Data Collection

2.3.1. Growth Parameters

Photosynthetically active radiation and leaf area index and were recorded using Accupar LP-80 ceptometer (Decagon Devices, Pullman, WA, USA). Leaf chlorophyll content was measured using SPAD 502 chlorophyll meter (Konica Minolta, Tokyo, Japan). The meter was used to clip the upper, middle and lower portion of five new fully expanded leaves per hill and their average was recorded. Plant dry matter accumulation was determined by randomly uprooting plants from six hills using a shovel from each experimental plot, excluding the border rows, and then divided into three parts namely; roots, tubers, and shoot (stem and leaves). The organs were washed with clean water and then kept in an oven at a temperature of 80 °C to a constant weight. Total plant dry matter was determined as the sum of tuber, root and shoot dry matter accumulations. Crop growth rate (g m^{-2} day^{-1})

was determined as the ratio of the difference between shoot dry matter at the seedling stage and flowering stage to the time intervals between the two stages.

$$\text{Crop Growth Rate (g m}^{-2}\text{ day}^{-1}\text{)} = \text{shoot dry matter at the seedling stage} - \text{shoot dry matter at flowering stage/time intervals between seedling stage and flowering stage} \quad (1)$$

2.3.2. Yield Parameters

Tubers from six hills, excluding the border rows, were randomly selected after harvest and used to determine yield components, such as tuber number, distribution of tuber size in weight, specific gravity, and harvest index. Tuber number per hill was obtained by manually counting all the tubers from the six hills and their average was recorded in grams per hill. Tuber size distribution in weight was taken by grouping all the tubers per hill into small, medium and large sizes in weight. Tubers that weighed between 25–38 g, 39–75 g, and above 75 g were classified as small, medium and large tuber sizes, respectively [39]. Harvest index was recorded as the ratio of tuber biomass to total plant biomass. Economic tuber yield was measured by weighing tubers from the net plot harvested area that were greater or equal to 39 g, free from disease and insect attack, and expressed as tons per hectare. Biological tuber yield was obtained by weighing all the tubers from the net plot harvested area, including tubers less than 39 g, diseased and deformed tubers, and expressed as tons per hectare. Profit margin was computed as the difference between cultivation cost and gross income per treatment. Cultivation cost is the sum of the cost of potato seeds, plastic film mulch, fertilizer, and labor per hectare. Gross income was calculated by extrapolating the price of potato per kilogram to a hectare.

2.3.3. Tuber Quality Parameters

Specific gravity of potato tubers was computed using the weight in air and weight in water method [40]. Briefly, 5 kg of tubers were put in a mesh bag and first weighed in air and then weighed in water. The tuber specific gravity was calculated by the formula below;

$$\text{Specific gravity (g cm}^{-3}\text{)} = \text{Weight in air/Weight in air} - \text{Weight in water} \quad (2)$$

Tuber starch content was determined using the gravity method whereas the percentage of tuber protein content was determined according to AOAC [41].

2.3.4. Soil Sampling and Analysis

Soil samples were collected after the 2019 harvest at five different sampling points at a depth of 0–20 cm in each experimental plot. The samples were then bulked to form a composite sample. The composite samples were air dried for 10 days after removing plant debris, stones, animals, and visually detectable fauna and then sieved through 1 mm and 0.15 mm meshes before soil chemical analysis. Soil pH was measured in a 1:2.5 water suspension using a portable pH meter with a glass electrode (Shanghai Precision and Scientific Instrument Company Limited, China). Total soil nitrogen concentration was determined using an Elemental Analyzer (vario MACRO cube, Elementar Analysensysteme GmbH, Germany). Soil organic carbon was determined using the potassium dichromate digestion method [42]. The bulk density of the soil was calculated as the ratio of oven-dry soil weight to soil volume. The total porosity of the soil was calculated by subtracting the ratio of bulk density to particle density from 1 and expressed as a percentage [43].

$$\text{Soil total porosity (\%)} = 1 - \text{soil bulk density/soil particle density x 100} \quad (3)$$

2.4. Statistical Data Analysis

Data collected were analyzed using SPSS software version 21 (IBM Corp., Chicago, IL, USA). Treatment means were subjected to one-way analysis of variance (ANOVA) and the least significant difference (LSD) test at the 5% probability level was used to compare the means. Figures were drawn using GraphPad Prism 6 (GraphPad Software, Inc., San Diego, CA, USA) whereas tables were drawn with Microsoft Office Word version 365 (Microsoft Corporation, Redmond, Washington, U.S).

3. Results

3.1. Effects of Straw Return and Nitrogen Rate on Potato Growth and Development

Potato growth and development were significantly affected by nitrogen rate with and without straw return in the 2018 and 2019 seasons (Figures 1–3). At the same N rate, treatments without straw produced better vegetative growth than treatments with straw in 2018; however, the opposite trend was observed in the 2019 season. Potato dry matter accumulation (DM) at harvest varied significantly by N treatments with and without straw in both seasons (Figure 1a–h). Accumulation of potato DM increased with an increase in N enrichment rate. The root DM ranged from 28.2 to 40.7 g m^{-2} in 2018 and 26.6 to 41.0 g m^{-2} in 2019, while tuber DM ranged from 251.6 to 380.8 g m^{-2} and 250.5 to 389.5 g m^{-2}, in 2018 and 2019 seasons, respectively. The shoot and total plant DM ranged from 51.9 to 142.1 g m^{-2} and 343.4 to 550.6 g m^{-2}, respectively in 2018, while in 2019 the shoot DM ranged from 50.9 to 152.0 g m^{-2} and total plant DM ranged from 328.0 to 570.3 g m^{-2}. Plants from MN + S treatment produced statistically similar root, tuber, shoot, and total plant DM values as plants from HN + S treatment in both seasons. Compared with the control, plants from MN + S treatment stimulated root DM (27.39% and 33.50%), tuber DM (31.54% and 35.69%), shoot DM (58.30% and 63.85%), and total plant DM (37.63% and 42.49%) in 2018 and 2019, respectively. Root DM was 4.96% higher in the 2018 season under the control than under the CK + S treatment; however, the latter produced 5.34% higher root dry matter in the 2019 season compared to the former.

Photosynthetically active radiation (PAR) and leaf chlorophyll content (CC) were significantly affected at flowering stage by N rate with and without straw in both seasons (Figure 2). An increase in N rate stimulated PAR and CC of leaves. The PAR ranged from 14.2 to 18.40 µmol m^{-2} s^{-1} in 2018 and 15.87 to 20.37 µmol m^{-2} s^{-1} in 2019 (Figure 2a,b). Plants from the MN + S treatment produced statistically similar PAR to plants from the HN treatment with and without straw; whereas, the CK with and without straw treatments produced the lowest PAR in both seasons. Photosynthetically active radiation was 18.60% and 19.11% higher under MN + S compared to the CK in the 2018 and 2019 seasons, respectively. Leaf CC ranged from 34.5 to 46.9 in 2018; while it ranged from 35.4 to 51.6 in 2019 (Figure 2c,d). Similarly, leaf CC under the MN + S treatment was statistically similar to the HN + S treatment in both seasons. Compared to the control, the MN + S treatment increased leaf CC by 19.41% in 2018 and 28.13% in 2019.

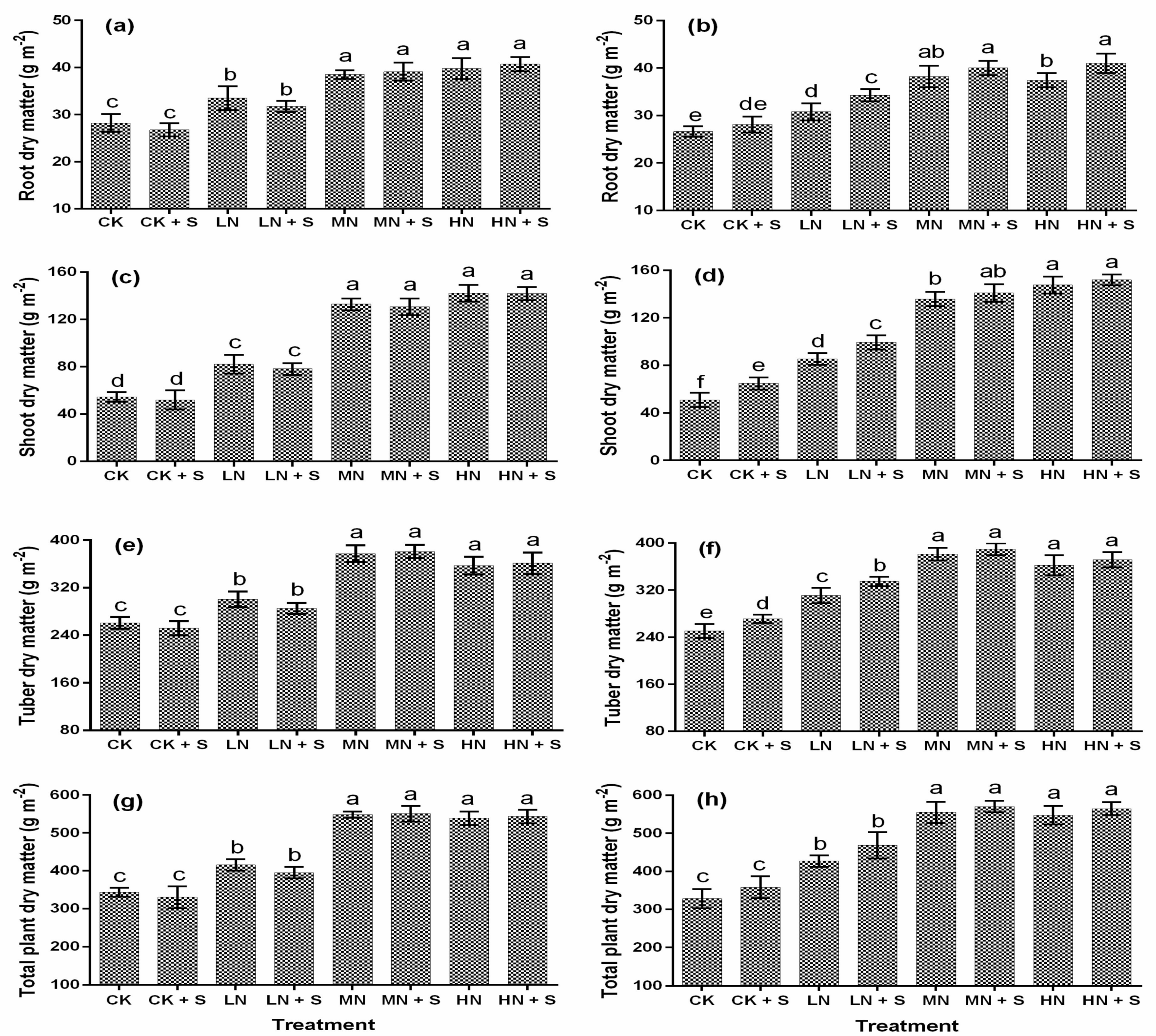

Figure 1. Effects of straw return and nitrogen rate on plant dry matter. (**a**); root dry matter in 2018 (**b**); root dry matter in 2019 (**c**); shoot dry matter in 2018 (**d**); shoot dry matter in 2019 (**e**); tuber dry matter in 2018 (**f**); tuber dry matter in 2019 (**g**); total plant dry matter in 2018 (**h**); total plant dry matter in 2019. Bars with the same letter within a chart are not significantly different from each other at 5% probability level. CK, no N enrichment; CK + S, no N enrichment with straw; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw. Bars represent ± standard error of means with four replications.

Leaf area index (LAI) at flowering stage and crop growth rate (CGR) were significantly affected by N rate with and without straw in both seasons. The LAI ranged from 2.05 to 3.33 in 2018 and 2.00 to 3.29 in 2019 (Figure 3a,b). Plants from MN and HN treatments with and without straw produced statistically similar LAI in both seasons. Leaf area index was 29.34% and 35.56% higher under MN + S treatment than the control in 2018 and 2019 seasons, respectively. However, the plants from the control produced significantly more LAI (13.85%) than the plants from the CK + S treatment in 2018. The CGR ranged from 1.62 to 3.44 g m^{-2} day^{-1} in 2018 and 1.69 to 3.59 g m^{-2} day^{-1} in 2019 (Figure 3c,d). Similarly, CGR was statistically at par among the MN and HN treatments with and without straw, whereas the control with and without straw return had the lowest CGR in both seasons. Compared to the control, MN + S treatment stimulated CGR by 41.88% in 2018 season and 50.32% in 2019 season.

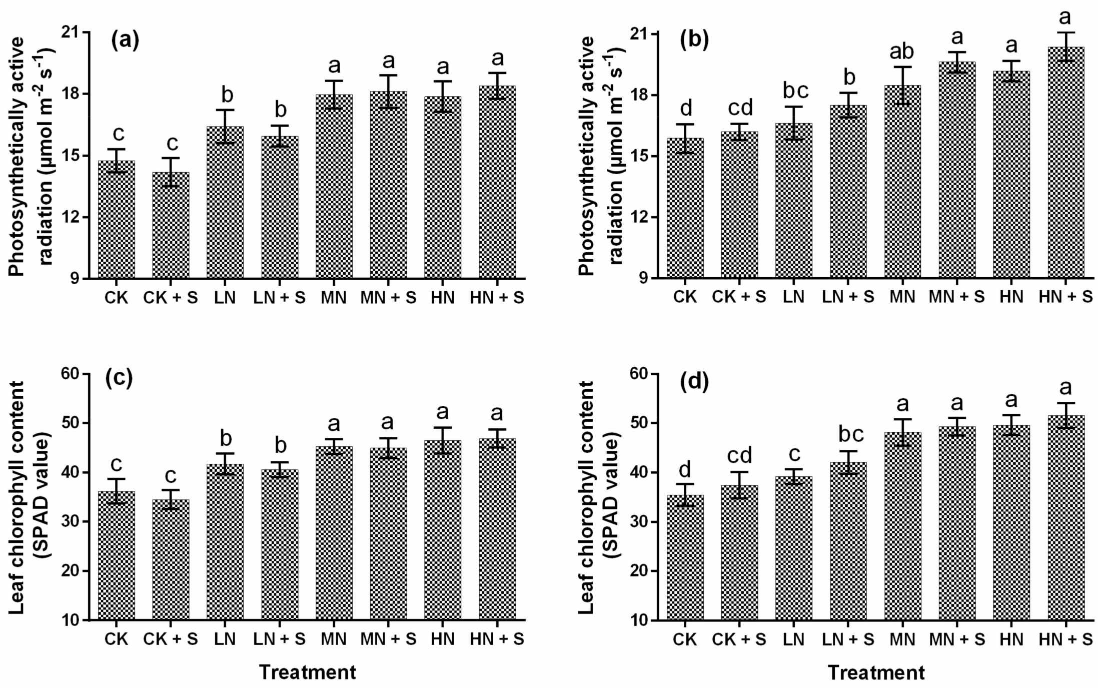

Figure 2. Effects of straw return and nitrogen rate on photosynthetically active radiation and leaf chlorophyll content. (**a**); photosynthetically active radiation in 2018 (**b**); photosynthetically active radiation in 2019 (**c**); leaf chlorophyll content in 2018 (**d**) leaf chlorophyll content in 2019. Bars with the same letter within a chart are not significantly different from each other at 5% probability level. CK, no N enrichment; CK + S, no N enrichment with straw; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw. Bars represent ± standard error of means with four replications.

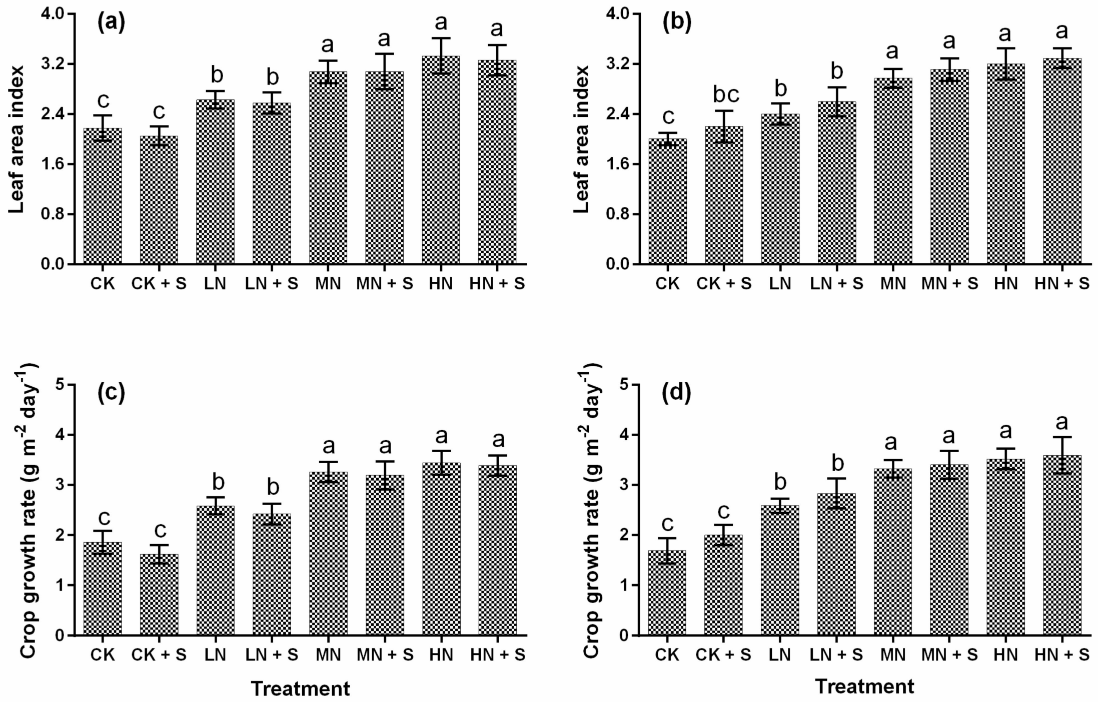

Figure 3. Effects of straw return and nitrogen rate on leaf area index and crop growth rate. (**a**); leaf area index in 2018 (**b**); leaf area index in 2019 (**c**); crop growth rate in 2018 (**d**); crop growth rate in 2019. Bars with the same letter within a chart are not significantly different from each other at 5% probability level. CK, no N enrichment; CK + S, no N enrichment with straw; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw. Bars represent ± standard error of means with four replications.

3.2. *Effects of Straw Return and Nitrogen Rate on Potato Tuber Yield and Yield Components*

Tuber size distribution was significantly varied by nitrogen rate and straw return in the 2018 and 2019 seasons (Table 3). The distribution of tuber size by weight increased with increasing N rate. Small, medium and large tuber sizes in weight ranged from 14.4 to 25.0 g hill^{-1}, 102.7 to 131.7 g hill^{-1}, and 129.7 to 247.4 g hill^{-1} in 2018, respectively. After the 2019 harvest, small tuber size in weight ranged from 13.6 to 30.0 g hill^{-1}, medium tuber size ranged from 92.9 to 130.5 g hill^{-1}, and large tuber size ranged from 141.5 to 259.5 g hill^{-1}. Plants from MN + S treatment produced statistically similar tuber size distributions to plants from the HN with and without straw in both seasons; while the control with and without straw recorded significantly the lowest tuber size distribution in weight. Compared to the control, the MN + S treatment stimulated medium and large tuber size in weight by 18.10% and 41.67% in 2018 and 27.82% and 45.47% in 2019, respectively. The number of tubers per hill was significantly affected by the treatments in both seasons. The number of tubers per hill ranged from 7 to 9 in 2018 and 7 to 10 in 2019 (Table 4). Plants from the MN + S treatment produced the highest number of tubers per hill, while the control with and without straw significantly produced the lowest number of tubers per hill in both seasons. Tuber number per hill was 22.22% and 30.00% higher under MN + S treatment than control in 2018 and 2019 seasons, respectively.

Table 3. Effects of straw return and nitrogen rates on tuber size distribution of potato in 2018 and 2019 seasons.

Treatment	Small Tuber Size (g hill^{-1}) 2018	Small Tuber Size (g hill^{-1}) 2019	Medium Tuber Size (g hill^{-1}) 2018	Medium Tuber Size (g hill^{-1}) 2019	Large Tuber Size (g hill^{-1}) 2018	Large Tuber Size (g hill^{-1}) 2019
CK	14.4 ± 1.15 b	18.6 ± 0.69 cd	102.7 ± 4.83 c	92.9 ± 6.94 c	144.3 ± 8.30 d	141.5 ± 9.78 c
CK + S	16.4 ± 0.35 b	13.6 ± 1.29 d	105.5 ± 5.64 bc	109.8 ± 4.20 bc	129.7 ± 8.49 d	144.8 ± 7.83 c
LN	23.3 ± 1.68 a	27.7 ± 1.05 a	123.8 ± 5.52 abc	124.4 ± 7.61 a	182.6 ± 7.34 b	180.7 ± 9.93 b
LN + S	21.5 ± 1.76 a	25.8 ± 1.40 b	136.5 ± 7.47 a	117.7 ± 4.79 ab	153.1 ± 9.79 c	199.2 ± 8.61 b
MN	25.0 ± 1.23 a	21.9 ± 1.45 bc	114.6 ± 5.89 abc	122.6 ± 6.75 a	243.5 ± 8.96 a	251.5 ± 6.58 a
MN + S	23.3 ± 1.63 a	18.6 ± 1.25 cd	125.4 ± 6.74 ab	128.7 ± 6.85 a	247.4 ± 8.56 a	259.5 ± 9.59 a
HN	23.8 ± 1.18 a	30.0 ± 1.28 a	126.7 ± 7.79 ab	123.9 ± 9.96 a	223.4 ± 8.88 a	236.8 ± 8.57 a
HN + S	22.6 ± 1.21 a	29.8 ± 1.85 a	131.7 ± 6.06 a	130.5 ± 7.44 a	231.1 ± 7.74 a	240.9 ± 9.43 a

Means with the same letter within a column are not significantly different from each other at 5% probability level. CK, no N enrichment; CK + S, no N enrichment with straw return; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw return; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw return; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw return. The ± means standard error of means at four replications.

Nitrogen rate with and without straw return had a significant effect on biological and economic tuber yield in both seasons (Table 4). At the same N rate, plants without straw treatments produced higher tuber yield than plants with straw treatments in 2018; however, the opposite trend was observed in the 2019 season. Biological tuber yield ranged from 19.03 to 28.66 t ha^{-1} in 2018 and 19.44 to 29.77 t ha^{-1} in 2019; while economic tuber yield ranged from 14.07 to 23.37 t ha^{-1} and 15.97 to 25.90 t ha^{-1} in 2018 and 2019 seasons, respectively. Plants from the MN + S treatment produced the optimum biological and economic tuber yield in both seasons, while the control with and without straw return had statistically the lowest tuber yield in both seasons. Biological tuber yield was 29.76% and 34.70% higher under MN + S treatment than the control in 2018 and 2019 seasons, respectively. Moreover, plants from MN + S treatment increased economic tuber yield by 34.73% in 2018 and 38.34% in 2019 compared to the control. Harvest index varied significantly by the treatments in both seasons (Table 5). An increase in N rate lowered the harvest index of potato. The harvest index ranged from 0.45 to 0.54 in 2018 and 0.46 to 0.54 in 2019. Plants from the control increased the harvest index of potato by 16.67% and 14.81% in 2018 and 2019 seasons, respectively, compared to plants from the HN treatment.

Table 4. Effects of nitrogen rates and straw return on tuber number per hill, biological tuber yield and economic tuber yield of potato in 2018 and 2019 seasons.

Treatment	Tuber Number Hill^{-1}		Biological Tuber Yield (t ha^{-1})		Economic Tuber Yield (t ha^{-1})	
	2018	2019	2018	2019	2018	2019
CK	7 ± 0.81 b	7 ± 0.50 c	20.13 ± 0.81 c	19.44 ± 1.93 c	15.24 ± 1.07 c	15.97 ± 1.42 e
CK + S	7 ± 1.36 b	8 ± 0.62 bc	19.03 ± 1.36 c	20.05 ± 0.92 c	14.07 ± 0.79 c	16.65 ± 1.21 de
LN	8 ± 1.05 ab	8 ± 0.60 bc	23.61 ± 1.05 b	24.49 ± 1.35 b	19.27 ± 1.07 b	20.36 ± 1.41 cde
LN + S	7 ± 0.80 b	9 ± 0.67 ab	22.98 ± 0.80 b	25.52 ± 1.11 ab	18.82 ± 0.93 b	21.14 ± 1.30 bcd
MN	9 ± 1.06 a	9 ± 0.76 ab	28.30 ± 1.06 a	28.99 ± 1.31 a	23.13 ± 1.01 a	24.29 ± 1.97 abc
MN + S	9 ± 1.17 a	10 ± 0.60 a	28.66 ± 1.17 a	29.77 ± 1.71 a	23.35 ± 0.90 a	25.90 ± 0.93 a
HN	8 ± 1.18 ab	9 ± 0.74 ab	27.32 ± 1.18 a	27.78 ± 1.28 ab	22.62 ± 0.98 a	24.07 ± 2.07 abc
HN + S	8 ± 1.15 ab	10 ± 0.85 a	28.48 ± 1.15 a	29.26 ± 1.45 a	23.37 ± 0.92 a	25.37 ± 1.23 ab

Means with the same letter within a column are not significantly different from each other at 5% probability level. CK, no N enrichment; CK + S, no N enrichment with straw; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw. The ± means standard error of means at four replications.

Table 5. Effects of nitrogen rates and straw return on harvest index, profit margin and benefit–cost ratio of potato for 2018 and 2019 seasons.

Treatment	Harvest Index		Profit Margin (USD)		Benefit Cost Ratio	
	2018	2019	2018	2019	2018	2019
CK	0.54 ± 0.004 a	0.54 ± 0.007 a	2273.72	2030.29	1.49	1.44
CK + S	0.53 ± 0.005 a	0.53 ± 0.015 a	1839.44	2189.15	1.39	1.47
LN	0.52 ± 0.014 a	0.52 ± 0.015 a	3445.44	3747.15	1.75	1.81
LN + S	0.52 ± 0.012 a	0.52 ± 0.006 a	3172.29	4043.15	1.67	1.86
MN	0.49 ± 0.004 b	0.47 ± 0.008 b	5032.01	5268.58	2.08	2.13
MN + S	0.48 ± 0.003 bc	0.47 ± 0.016 b	5111.15	5491.72	2.08	2.16
HN	0.45 ± 0.005 d	0.46 ± 0.004 b	4653.15	4810.86	1.99	2.02
HN + S	0.46 ± 0.001 cd	0.47 ± 0.008 b	4993.72	5261.15	2.05	2.10

Means with the same letter within a column are not significantly different from each other at 5% probability level. CK, no N enrichment; CK + S, no N enrichment with straw; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw. The ± means standard error of means at four replications.

3.3. Effects of Straw Return and Nitrogen Rate on Profit Margin, Benefit Cost Ratio and Potato Tuber Quality

Profit margin ranged from USD 1839.44 to USD 5111.15 in 2018 and USD 2030.29 to USD 5491.72 in the 2019 season (Table 5). Plants from the control increased the profit margin by 19.10% compared to plants from the CK + S treatment in 2018, but plants from the latter treatment stimulated the profit margin by 7.26% compared to the control in 2019. The profit margin was 55.51% and 63.03% under the MN + S treatment in the 2018 and 2019 seasons, respectively, compared to the control. The benefit: cost ratio (B:C) ranged from 1.39 to 2.08 in 2018 and 1.44 to 2.16 in the 2019 season (Table 5). Similarly, B:C ratio increased by 28.37% and 33.33% in plants from MN + S treatment compared to the control in 2018 and 2019 seasons, respectively. Nitrogen rate with and without straw did not significantly affect specific gravity and starch content of potato tubers in both seasons (Table 6). However, protein content of tubers varied significantly by the treatments in both seasons (Table 6). It ranged from 8.28% to 12.24% in 2018 and 8.11% to 12.73% in 2019. Protein content was significantly stimulated with increasing N rate. Compared to the control, HN + S treatment increased protein content by 30.23% in 2018 and 36.29% in the 2019 season.

Table 6. Effects of nitrogen rates and straw return on specific gravity, starch content, and protein content of potato for 2018 and 2019 seasons.

Treatment	Specific Gravity (g cm^{-3})		Starch Content (%)		Protein Content (%)	
	2018	2019	2018	2018	2018	2019
CK	1.100 ± 0.001 a	1.091 ± 0.007 a	18.1 ± 0.56 a	15.7 ± 1.44 a	8.54 ± 0.25 c	8.11 ± 0.13 d
CK + S	1.100 ± 0.003 a	1.091 ± 0.010 a	18.1 ± 0.77 a	15.7 ± 1.36 a	8.28 ± 0.22 c	8.76 ± 0.16 cd
LN	1.097 ± 0.002 a	1.089 ± 0.013 a	17.3 ± 0.80 a	15.3 ± 1.67 a	9.07 ± 0.46 c	9.62 ± 0.31 bc
LN + S	1.097 ± 0.004 a	1.089 ± 0.012 a	17.3 ± 1.04 a	15.3 ± 1.00 a	8.70 ± 0.38 c	9.71 ± 0.32 bc
MN	1.095 ± 0.002 a	1.086 ± 0.007 a	16.8 ± 0.56 a	14.5 ± 0.52 a	10.58 ± 0.35 b	10.81 ± 0.72 b
MN + S	1.095 ± 0.002 a	1.086 ± 0.003 a	16.8 ± 0.49 a	14.5 ± 0.91 a	10.68 ± 0.35 b	10.88 ± 0.55 b
HN	1.091 ± 0.001 a	1.083 ± 0.008 a	15.7 ± 0.43 a	13.7 ± 0.61 a	12.11 ± 0.40 a	12.35 ± 0.26 a
HN + S	1.091 ± 0.002 a	1.083 ± 0.006 a	15.7 ± 0.70 a	13.7 ± 1.21 a	12.24 ± 0.16 a	12.73 ± 0.47 a

Means with the same letter within a column are not significantly different from each other at 5% probability level. CK, no N enrichment; CK + S, no N enrichment with straw; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw. The ± means standard error of means at four replications.

3.4. Effects of Straw Return and Nitrogen Rate on Soil Physicochemical Properties after 2019 Harvest

Nitrogen rate with and without straw return significantly affected soil physicochemical properties after harvest of 2019 season (Table 7). Soil organic carbon (SOC) and total nitrogen concentrations varied significantly among the treatments. The SOC content ranged from 9.87 to 11.98 g kg^{-1}, while total N ranged from 1.25 to 1.65 g kg^{-1}. Soil organic carbon content was significantly higher in treatments with straw than in treatments without straw. There was no significant difference between HN +S and MN + S treatments in terms of SOC and total N; however, MN + S treatment increased SOC by 17.41% and total N by 19.87% compared to the control. Straw return significantly affected soil bulk density and porosity, whilst nitrogen rate significantly reduced soil pH. Soil bulk density, porosity and pH ranged from 1.316 to 1.344 g cm^{-3}, 49.06 to 50.34%, and 8.04 to 8.14, respectively. Both soil pH and bulk density decreased with increasing N rate. In contrast to soil pH and bulk density, increasing N rate increased soil porosity. Treatments with straw had statistically similar soil porosity and bulk density values. Compared to the control, the MN + S treatment decreased soil pH (1.11%) and bulk density (1.56%); however, it increased soil porosity by 2.10%.

Table 7. Effects of nitrogen rates and straw return on soil physicochemical properties after 2019 harvest.

Treatment	SOC (g kg^{-1})	Total Nitrogen (g kg^{-1})	Porosity (%)	Soil pH	Bulk Density (g cm^{-3})
CK	9.87 ± 0.58 b	1.25 ± 0.018 e	49.06 ± 0.13 c	8.14 ± 0.2 a	1.343 ± 0.003 a
CK + S	11.72 ± 0.65 a	1.28 ± 0.027 e	50.15 ± 0.05 a	8.13 ± 0.01 a	1.321 ± 0.001 c
LN	9.90 ± 0.44 b	1.37 ± 0.007 d	49.28 ± 0.18 c	8.12 ± 0.02 ab	1.344 ± 0.005 a
LN + S	11.86 ± 0.57 a	1.40 ± 0.019 d	50.03 ± 0.12 ab	8.10 ± 0.01 ab	1.323 ± 0.003 bc
MN	10.05 ± 1.34 b	1.52 ± 0.024 c	49.29 ± 0.12 c	8.08 ± 0.02 bc	1.344 ± 0.003 a
MN + S	11.95 ± 0.63 a	1.56 ± 0.029 bc	50.11 ± 0.23 a	8.05 ± 0.04 c	1.322 ± 0.006 c
HN	10.03 ± 0.50 b	1.63 ± 0.025 ab	49.36 ± 0.19 bc	8.05 ± 0.14 c	1.342 ± 0.005 ab
HN + S	11.98 ± 0.60 a	1.65 ± 0.020 a	50.34 ± 0.21 a	8.04 ± 0.02 c	1.316 ± 0.006 c

Means with the same letter within a column are not significantly different from each other at 5% probability level. SOC, soil organic matter. CK, no N enrichment; CK + S, no N enrichment with straw; LN, 75 kg Nha^{-1}; LN + S, 75 kg Nha^{-1} with straw; MN, 150 kg Nha^{-1}; MN + S, 150 kg Nha^{-1} with straw; HN, 300 kg Nha^{-1}; HN + S, 300 kg Nha^{-1} with straw. The ± means standard error of means at four replications.

4. Discussion

4.1. Effects of Straw Return and Nitrogen Rate on Growth and Development of Potato

Nitrogen enrichment enhances the growth and development of potato plants [44–46]. In this study, N enrichment with and without straw return significantly increased the vegetative growth of potato in both seasons. This may be due to the additional nitrogen from the fertilizer and the nutrients released from the maize straw after decomposition to the native nutrients in the soil. At the same N rate, plants without straw produced better vegetative growth than plants with straw in the first season; however, an opposite trend was observed in the second season; probably due to slow mineralization and immobilization of nutrients during the first season of straw return. Soil microbes immobilize plant nutrients during the initial stages of decomposition of plant residues [31], which hinders plant growth and development during these stages. The maize straw had a C:N ratio above 46 (Table 2), and when such organic material is returned to the soil, microbes use the available N in the soil as an energy source (immobilization) to decompose the organic material, which impairs N availability [19,47,48]. Low quality plant residues (C:N ratio <24) have a slow rate of mineralization, which in turn hinders the availability of plant nutrients in the initial stages of decomposition [19,49,50]. However, the addition of inorganic N after straw return increased the available N content in the soil, which hindered N immobilization during decomposition and consequently facilitated mineralization of nutrients from straw [24]. This could explain why the plants without straw showed better vegetative growth in the first season than those with straw at the lower N rate (0 and 75 kg ha^{-1}). Nitrogen enrichment after straw return facilitates decomposition rate [51]. Plants from HN + S treatment produced the best vegetative growth, probably due to their high leaf CC, PAR, and LAI, which might have increased the production of assimilate for growth and development of potato. This finding concurs with Wen et al. [52] who noted that leaf area index correlates with photosynthetic capacity, thereby increasing vegetative growth of plants.

4.2. Effects of Straw Return and Nitrogen Rate on Potato Tuber Yield and Yield Components

Nitrogen enrichment has a positive and significant effect on the yield and yield components of potato [52,53]. However, excessive N fertilization reduces the yield of potato tubers [53,54] and pollutes the environment [55]. Therefore, the application of optimum N fertilization rate stimulates tuber yield and profit margin of potato. In this study, plants from the N fertilized treatments with and without straw produced significantly higher potato tuber yield and yield parameters than plants from the control. This may be attributed to higher accumulation of roots and shoot dry matter compared to the control and therefore may have affected source capacity and consequently increased tuber yield. Nitrogen enrichment promotes potato source capacity, which stimulates tuber yield [45,56]. Our results also showed that excessive N fertilization (HN) increased tuber yield compared to the LN and control, but caused a reduction in tuber yield compared to the MN treatment. Thus, excessive N fertilization increases tuber yield but does not necessarily result in optimum potato production. This result is in agreement with previous studies [54,57–60]; however, our results do not agree with those of Kumar et al. [44] who observed optimum tuber yield at the highest N rate (360 kg ha^{-1}). The discrepancy between the previous study and the present study may be attributed to the nutrient status of the soils used. The plants from the MN + S treatment produced the best tuber yield; partly due to their high tuber number and large tuber size in weight (Tables 3 and 4). In addition, the MN + S treatment improved soil physicochemical properties (Table 7), which increased nutrient availability and consequently stimulated tuber yield. Harvest index decreased with an increase in N rate, probably due to the high vegetative growth of the N fertilized plants. Moreover, N enrichment delayed the maturity (senescence) of potato plants [53,61,62], which might have decreased the harvest index of fertilized plants.

4.3. Effects of Straw Return and Nitrogen Rate on Tuber Quality and Profit Margin of Potato

Nitrogen enrichment influences specific gravity, starch content and protein content of potato [57,63,64]. A tuber with low specific gravity has a dark frying color and low chip yield, and consequently requires more time and oil for processing, whereas tubers with high specific gravity are prone to increased bruising [65]. In this study, N enrichment with and without straw return had no significant effect on potato specific gravity and starch content, which is consistent with previous studies [54,66]. Mosley and Chase [65] and

Love et al. [67] documented that potato specific gravity is mainly controlled by the genetic makeup of the cultivar. However, increasing N enrichment rate with and without straw slightly decreased the specific gravity and protein content of potato tuber. Lin et al. [63] and Ahmed et al. [57] found a decrease in specific gravity and starch content of potato tubers with an increase in N rate, probably due to the high carbon requirement of N assimilation. Protein content of tubers increased with an increase in N enrichment rate with and without straw; this result is consistent with previous studies [59,64,68].

The profit margin increased with increasing N enrichment rate with and without straw up to a point (150 kg N ha^{-1}) and then decreased beyond this point; this result supports those reported by Sriom et al. [60], Love et al. [69] and Nurmanov et al. [70]. The profit margin of potato increases with increasing N rate up to a point (100 kg N ha^{-1}) and then decreases beyond this point [69]. The MN + S treatment recorded the highest profit margin and B:C ratio, probably due to its high economic tuber yield (Table 4), which increased the net returns. This could explain why the control with and without straw return had the lowest profit margin and B:C ratio.

4.4. Effects of Straw Return and Nitrogen Rate on Soil Physicochemical Properties

Straw return and nitrogen enrichment play a significant role in improving the physicochemical properties of soils [22,51,71,72]. In this study, nitrogen treatments with straw significantly increased soil organic carbon content and porosity, whilst decreased bulk density compared to treatments without straw at the same N rate. This result is in agreement with previous studies, which indicated that straw return reduced soil bulk density [73,74], and increased soil porosity [75,76] and organic carbon content [51,77,78]. Treatments with straw may reduce soil erosion partly due to their low soil bulk density and high porosity [79]. In addition, straw return increased SOC and total N content (Table 7), which in turn increased aggregate stability by promoting interparticle cohesion, soil aggregation and the ability of the soil to resist erosion [80]. Kavian et al. [80] found that soil erosion was positively and significantly correlated with both SOC and total N content. Nitrogen enrichment also improved soil chemical properties by increasing soil total N content and lowering soil pH; this result is in agreement with previous studies [81–83]. Soil pH decreased with increasing N rate, which was partly due to the production and release of hydrogen ions into the soil solution during nitrification [84]. In addition, Lu et al. [85] pointed out that N enrichment increases the leaching of basic cations, such as Ca^{2+} and Mg^{2+} into the charge balance of the soil solution, thereby lowering the soil pH. A similar observation has been reported in previous studies [81–83]. Nitrogen treatments after maize straw return improved the soil fertility compared to the control with and without straw return. This can be attributed to the rapid mineralization of the nutrients from the straw due to the additional inorganic N fertilizer applied to the soil native N. Tejada and Benítez [24] documented that returning of crushed maize straw resulted in N immobilization, while the addition of inorganic N resulted in net mineralization. Soil nitrogen availability plays a major role in the decomposition of organic matter, such as plant residues. Soil N concentration affects the C:N ratio of the soil, which regulates the balance between immobilization and mineralization of nutrients [24]. Nitrogen enrichment after straw return facilitates decomposition rate [51]. Moreover, Prescott [32] reported that N enrichment stimulates the decomposition of plant residues with low lignin content (<12%), while it slows decomposition of residues with high lignin content (>18%). The lignin content of the maize straw used in the present study was less than 11.2% (Table 2); this may explain why N enrichment after straw return enhanced the decomposition and mineralization of nutrients from the straw, thereby improving soil fertility.

5. Conclusions

Straw return and nitrogen enrichment improved soil physicochemical properties by increasing soil organic carbon, total nitrogen, and soil porosity, and by lowering pH and bulk density of the alkaline soil. As a result, potato growth, tuber yield, tuber quality, and profit margin were significantly stimulated by N enrichment with straw return. Excessive N enrichment (300 kg ha^{-1}) increases tuber yield of potatoes, but does not necessarily result in optimum potato production. Nitrogen enrichment after straw return facilitates the rate of decomposition and mineralization of nutrients from the straw, which improves soil fertility. The results of the study indicated that nitrogen enrichment after maize straw return is an effective and sustainable practice for stimulating potato tuber yield and quality, profit margin, as well as improving soil fertility to promote sustainable agriculture development. Straw return has been associated with increased CO_2 emission; however, this study did not examine the effect of different N fertilization rates on CO_2 emission after straw return. In addition, straw decomposition dynamics and N immobilization rate were not determined in our study; however, measuring these parameters will lead to a better understanding of the positive effect of N enrichment after straw return on potato performance and soil physicochemical properties. Therefore, future studies should focus on how different N fertilization rates affect straw decomposition, N immobilization rate, CO_2 emission, and N use efficiency of potato.

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