Effects of Different Vegetable Cultivation Modes on Total Nitrogen, Total Phosphorus, and COD in Soil Leachate (Postprint)

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Abstract

Based on the long-term fixed-site experiment of organic vegetables in solar greenhouses initiated in 2002 at the Quzhou Experimental Station of China Agricultural University, leachate water from a depth of 1 m was collected using a lysimeter device. By measuring total nitrogen, total phosphorus, and chemical oxygen demand (COD) in soil leachate water from spring-crop eggplant and autumn-crop celery in 2014, nutrient leaching under different vegetable cultivation modes (organic, integrated, and conventional) was studied. The results showed: the total nitrogen leaching loss in the organic mode for the two crop seasons combined was 137.02 kg · hm 2, which was 12.0% and 25.9% lower than that in the integrated and conventional modes, respectively; the total phosphorus leaching loss for the two crop seasons combined was 18.23 kg · hm 2, which was 51.2% and 119.9% higher than that in the integrated and conventional modes, respectively; the COD of leachate water for the two crop seasons combined was 856.99 kg · hm 2, which was 32.4% and 3.1% higher than that in the integrated and conventional modes, respectively. The temporal variation trends of total nitrogen, total phosphorus, and COD in leachate water differed significantly among the three modes. For spring-crop eggplant, total nitrogen leaching loss remained at a relatively high level in the early stage, peaked after topdressing, then decreased rapidly, and fluctuated at a low level from June onward; total phosphorus leaching loss changed relatively smoothly, showing a trend of first increasing and then decreasing, reaching a peak between June and July; COD of leachate water decreased slightly in the early stage, reached its minimum value before topdressing, and showed a gradual upward trend from May to the end of the eggplant season. In summary, the organic cultivation mode demonstrated advantages over the integrated and conventional modes in reducing nitrogen leaching, but significantly increased the risk of phosphorus leaching and, to a certain extent, increased the COD of leachate water.

Full Text

Effect of Vegetable Cropping System on Total Nitrogen, Phosphorus and COD in Farmland Leachate

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Abstract

Based on a long-term organic vegetable experiment initiated in 2002 at the Quzhou Experimental Station of China Agricultural University, this study investigated soil nutrient leaching under different vegetable cropping systems. Using lysimeter devices to collect leachate from 1 m depth, we measured total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD) in leachate from spring eggplant and autumn celery crops in 2014. Results showed that the organic system had a cumulative TN leaching loss of 137.02 kg·hm ^{2} across both seasons, which was 12.0% and 25.9% lower than the integrated and conventional systems, respectively. However, TP leaching loss in the organic system reached 18.23 kg·hm ^{2}, representing increases of 51.2% and 119.9% compared to the integrated and conventional systems. COD in leachate from the organic system totaled 856.99 kg·hm ^{2}, exceeding the integrated and conventional systems by 32.4% and 3.1%, respectively. The temporal trends of TN, TP, and COD in leachate differed significantly among the three systems. During the spring eggplant season, TN leaching remained high in the early stage, peaked after top dressing, then declined rapidly and fluctuated at low levels after June. TP leaching showed a relatively smooth pattern, first increasing then decreasing, with peaks occurring between June and July. COD initially decreased slightly, reached its minimum before top dressing, and then gradually increased from May until the end of the eggplant season. In summary, the organic system demonstrated advantages in reducing nitrogen leaching compared to integrated and conventional systems, but significantly increased phosphorus leaching risk and elevated leachate COD to some extent.

Keywords: Solar greenhouse; Vegetable; Cropping system; Soil water leaching; Total nitrogen; Total phosphorus; Chemical oxygen demand (COD)

Introduction

China currently leads the world in greenhouse vegetable cultivation area. While greenhouse production efficiently utilizes environmental factors, extends growing seasons, and increases yields, it is also characterized by excessive nitrogen and phosphorus inputs and imbalanced organic fertilizer application. Research has shown that long-term irrational fertilization causes soil nutrients to leach into deeper soil layers under rainfall or irrigation, posing risks to groundwater environments. Long-term fertilizer experiments offer unique advantages over conventional trials by systematically revealing how different fertilization regimes affect soil physical and chemical properties, providing a decision-making basis for sustainable agriculture.

Numerous domestic and international studies have focused on long-term fertilization effects, primarily examining crop-soil interactions. Research demonstrates that long-term application of organic and chemical fertilizers continuously increases soil nitrogen and phosphorus content, with organic manure showing superior effects that intensify with application rate. Combined organic-chemical fertilization significantly improves soil physical properties and enzyme activities, whereas long-term chemical fertilizer alone reduces soil pH and enzyme activity. Soil enzyme activity correlates positively with soil organic matter and nutrient content. Continuous organic manure application effectively increases soil total nitrogen, microbial biomass nitrogen, potential mineralizable nitrogen, and particulate organic nitrogen, helping maintain soil nitrogen supply capacity. Long-term organic fertilization also significantly increases various phosphorus fractions, while organic-chemical combinations help activate soil phosphorus and increase available phosphorus content. Soil organic matter content increases with organic manure application rates and shows an upward trend over years.

Due to shallow root distribution, heavy irrigation, and excessive nitrogen application, vegetable production is prone to nitrogen leaching and environmental pollution. Studies indicate that severe groundwater nitrate pollution is primarily associated with vegetable cultivation with high chemical fertilizer inputs, with nitrate levels significantly higher in vegetable-growing areas than in grain crop regions. Compared to chemical fertilizers, organic manure reduces soil profile nitrate nitrogen content and slows accumulation peak migration, though irrational application can also cause substantial nitrogen leaching. Organic manure activates various phosphorus forms, increasing soil total and available phosphorus content. Long-term heavy organic manure application in vegetable fields increases soil total and available phosphorus, reduces phosphorus adsorption capacity, and promotes phosphorus leaching losses.

Greenhouse vegetable fields feature high fertilizer inputs and high proportions of organic manure. Long-term heavy application of organic and chemical fertilizers significantly affects soil nutrient content and physicochemical properties, influencing nitrogen and phosphorus leaching and increasing nutrient loss risk. However, few studies have compared soil nutrient leaching between organic and conventional greenhouse vegetable production systems under long-term fertilization. This study, based on a long-term organic vegetable experiment at the Quzhou Experimental Station, investigated cumulative nitrogen, phosphorus, and COD leaching and their dynamic changes under different cropping systems (organic, integrated, conventional) to provide insights for controlling nutrient leaching risks and developing safe, efficient, and environmentally friendly greenhouse vegetable production models.

Materials and Methods

1.1 Experimental Site

The experiment was conducted at the Quzhou Experimental Station of China Agricultural University in Quzhou County, Handan City, Hebei Province (36°52 N, 115°01 E). Initiated in March 2002, this long-term study focuses on organic vegetable production. The region has a temperate semi-humid monsoon climate with abundant light, heat, and water resources, but strong monsoon influence brings cold, dry winters and warm, rainy summers. Annual precipitation averages 604 mm, supporting a double-cropping system. The solar greenhouse used in the experiment was arched, 52 m long, 7 m wide, covering approximately 0.04 hm^2. The soil was a reclaimed salinized fluvo-aquic soil that had been under vegetable cultivation for many years. Initial soil nutrient conditions before the experiment are shown in .

1.2 Experimental Design

Three treatments were established: (1) **Organic system (ORG)**: Following IFOAM Basic Standards, using only compost with physical and biological pest control supplemented by biological agents; (2) **Integrated system (INT)**: Using reduced chemical and compost inputs with biological/physical pest control, applying low-toxicity, low-residue pesticides only when necessary; (3) **Conventional system (CON)**: Using chemical fertilizers with small amounts of organic manure and urea top dressing, relying primarily on chemical pesticides for pest control. Chemical fertilizers included urea, calcium superphosphate, and potassium chloride (3:5:4 ratio). Compost consisted of cow manure, dry chicken manure, and straw treated with VT microbial agent.

Each cropping system was implemented in a separate greenhouse, divided into three 120 m^2 plots as replicates. In spring 2014, eggplant (*Solanum melongena* L., cultivar 'Bawangqie') grafted onto 'Toluobamu' rootstock was planted at 865 plants per greenhouse on February 20, harvested on September 15. In autumn 2014, celery (*Apium graveolens* L., cultivar 'Meiguo Xiqin') was planted at 11,000 plants per greenhouse on October 19, harvested in February 2015.

All three greenhouses used flood irrigation 13 times during the two seasons in 2014, with 975 $m^3 \cdot hm^{2}$ per event. Irrigation dates were: February 20, March 20, April 13, May 5, May 22, June 6, July 2, July 19, August 30, October 24, November 20, December 24, 2014, and January 24, 2015. Spring eggplant received base fertilizer on February 10 and top dressing on April 30 (5:1 ratio). Autumn celery received only base fertilizer on October 14. Nutrient application rates are detailed in .

1.3 Sampling Methods

Soil sampling: In each treatment plot, soil samples were collected from between plant rows using an auger at 0–40 cm depth in 20 cm increments. Five cores per plot were taken in a Z-pattern and mixed. Samples were air-dried after removing stones and plant residues for physicochemical analysis. Sampling occurred on February 8 and October 13, 2014.

Leachate collection: Lysimeter devices collected leachate at approximately 1 m depth. Before planting, a 0.5 m × 0.5 m × 1 m pit was dug in the center of each plot, with a sloped bottom (1-1.1 m depth) to accommodate the lysimeter. A 20 cm trench on one side held tubing, while a 0.11 m diameter, 1.6 m deep pit on the opposite side housed the collection vessel. Leachate was extracted 4–6 days after each irrigation, total volume recorded, and three 50 mL subsamples collected as replicates, stored in ice boxes and frozen at -20°C until analysis. Thirteen samples were collected across both seasons on: February 26, March 25, April 17, May 10, May 28, June 12, July 19, August 30, October 24, November 20, December 24, 2014, and January 30, 2015.

1.4 Analysis Methods

Total nitrogen was determined by alkaline potassium persulfate digestion-UV spectrophotometry; total phosphorus by ammonium molybdate spectrophotometry; and COD by rapid digestion-spectrophotometry. Leaching losses from the 100 cm soil layer were calculated using the formula: $P = \Sigma(Ci \times Vi) / A$, where P is nutrient loss (kg·hm ^{2}), Ci is concentration (g·mL ^{1}), Vi is leachate volume (mL), and A is greenhouse area (hm^{2}).

1.5 Data Processing

Data were processed using Microsoft Excel 2010. Statistical analysis and ANOVA were performed using SPSS v.20.0, and figures were created with SigmaPlot 12.0.

Results

2.1 Total Nitrogen Leaching

2.1.1 TN Leaching Amounts Total nitrogen leaching under different cropping systems is shown in [Figure 1: see original paper]. The conventional system showed the highest TN leaching during both spring eggplant (129.79 kg·hm ^{2}) and autumn celery (55.14 kg·hm ^{2}) seasons. For spring eggplant, the organic system (98.00 kg·hm ^{2}) was significantly lower than conventional and integrated systems, while the latter two showed no significant difference. For autumn celery, the integrated system had the lowest TN leaching (32.96 kg·hm ^{2}), with the organic system (39.02 kg·hm ^{2}) also significantly lower than conventional.

Combining data from and [Figure 1: see original paper], spring eggplant nitrogen inputs in conventional and integrated systems were 32.9% and 4.1% higher than in the organic system, while TN leaching was 32.4% and 25.3% higher, respectively. Autumn celery nitrogen inputs in conventional and integrated systems were 98.4% and 84.5% of the organic system, while TN leaching was 141.3% and 84.5% of the organic system, respectively. Overall, the organic system helped reduce nitrogen leaching, though autumn celery showed higher leaching likely due to highest nitrogen input. The conventional system consistently showed high nitrogen leaching, possibly due to high fertilizer inputs and faster nutrient release from chemical fertilizers compared to organic manure.

2.1.2 TN Leaching Dynamics During the spring eggplant season, all three systems maintained relatively high TN leaching in early growth stages, with notable peaks on March 25 and May 5 [Figure 2: see original paper]. This corresponded to base fertilizer application on February 10 and top dressing on April 30, with nitrogen moving downward during subsequent irrigations. After June, TN leaching decreased rapidly and remained low, likely due to vigorous eggplant growth increasing nitrogen uptake and reduced soil nitrogen from earlier leaching losses. The organic system maintained consistently lower and more stable TN leaching, probably due to slower nutrient release from organic manure. The conventional system showed the highest post-fertilization peaks, indicating rapid nutrient release and leaching susceptibility.

Due to celery’ s shorter growing season and lower winter evaporation, only four irrigations occurred during the autumn season. The leaching trend was similar to spring eggplant, with a peak on December 24 that decreased rapidly thereafter.

2.2 Total Phosphorus Leaching

2.2.1 TP Leaching Amounts Total phosphorus leaching in 2014 is presented in [Figure 3: see original paper]. Both seasons showed the highest TP leaching under organic system, followed by integrated, then conventional. During spring eggplant, organic and integrated systems leached 9.77 kg · hm ^{2} and 6.46 kg · hm ^{2}, respectively—111.0% and 39.5% higher than conventional. During autumn celery, organic and integrated systems leached 8.12 kg · hm ^{2} and 5.66 kg · hm ^{2}, respectively—121.9% and 54.6% higher than conventional, with significant differences among treatments.

Phosphorus inputs followed the order conventional > integrated > organic . Despite lowest phosphorus input, the organic system showed highest leaching, likely because organic manure introduced large amounts of easily mineralizable organic phosphorus while activating adsorbed soil phosphorus.

2.2.2 TP Leaching Dynamics Temporal phosphorus leaching patterns [Figure 4: see original paper] mirrored total amounts: conventional < integrated < organic. All systems showed low phosphorus leaching, probably due to strong soil phosphorus fixation, with most phosphorus converting to insoluble fixed forms and only minimal amounts entering soil solution. Spring eggplant TP leaching first increased then decreased, possibly because rising temperatures enhanced microbial activity, releasing poorly soluble phosphorus. In later growth stages, leaching decreased due to prior loss of water-soluble and activated phosphorus plus crop uptake.

2.3 Chemical Oxygen Demand

2.3.1 Leachate COD COD is an important indicator of organic pollution. Leachate COD under different systems is shown in [Figure 5: see original paper]. The integrated system showed the lowest COD across both seasons (451.71 kg · hm ^{2} for spring eggplant and 127.21 kg · hm ^{2} for autumn celery). During spring eggplant, organic system COD reached 658.78 kg · hm ^{2}, 45.8% and 6.87% higher than integrated and conventional systems, respectively. During autumn celery, conventional system COD was 215.10 kg · hm ^{2}, 69.1% and 8.5% higher than integrated and organic systems. Higher COD in the organic system likely resulted from large amounts of soluble organic matter introduced by organic manure. Interestingly, the conventional system showed higher COD than the integrated system despite lower organic manure input, requiring further investigation.

2.3.2 COD Dynamics Spring eggplant leachate COD showed a decreasing trend followed by a significant increase [Figure 6: see original paper], while autumn celery showed the opposite pattern. This likely relates to annual temperature variations: from March to August, rising temperatures and frequent irrigation enhanced microbial activity, gradually increasing soluble organic matter and COD; from November to January, lower soil temperatures reduced microbial activity, decreasing COD.

Discussion

The three treatments differed in nitrogen, phosphorus, and potassium inputs, but results demonstrate that the organic system effectively reduced soil nitrogen leaching, outperforming conventional and integrated systems. Previous research indicated that compared to integrated and conventional systems, organic production had lower nitrogen input but higher nitrogen output through crop uptake. From 2002 to 2014, total nitrogen content in 0–20 cm and 20–40 cm layers increased most markedly under organic system, followed by integrated, while conventional showed little change. This suggests organic systems reduce nitrogen loss while continuously improving soil fertility.

Organic nitrogen in manure has a lower proportion of easily leached nitrate nitrogen compared to chemical fertilizers, resulting in more stable TN leaching dynamics and lower total losses. Organic manure application increases soil organic matter and aggregate content, improving water retention and ion adsorption capacity, delaying nutrient release, and enhancing soil fertility preservation to reduce nitrogen leaching. However, excessive organic manure can increase nitrogen leaching—autumn celery in the organic system had 18.3% higher nitrogen input and 18.4% higher TN leaching than the integrated system, showing no advantage in leaching reduction.

Long-term organic manure application increased soil fertility, with available phosphorus before eggplant planting exceeding three times that of the conventional system. High available phosphorus increased leaching risk. TP leaching results confirm that organic systems significantly increased phosphorus leaching risk, with losses increasing as organic manure proportion increased. Despite lower phosphorus input, organic systems showed highest TP leaching, possibly because organic manure increased soil organic matter and microbial populations, including organic phosphorus mineralizing bacteria, promoting conversion to soluble phosphorus. Organic acids produced during manure decomposition can exchange with phosphate ions on soil particle surfaces, activating soil phosphorus and increasing dissolved phosphorus content. Studies by Xiao et al., Yu et al., and Chen et al. also showed organic manure significantly increased available phosphorus and promoted phosphorus leaching, with losses increasing with application rate.

After phosphorus fertilizer application, rapid chemical, physicochemical, and biochemical processes cause phosphorus to be quickly adsorbed by soil minerals or immobilized by microorganisms. TP leaching across the three systems was less than 1% to 5% of phosphorus input, indicating leaching does not cause major phosphorus loss, though long-term heavy phosphorus inputs lead to soil accumulation.

COD measures relative organic content in water. Few studies have examined leachate COD. Some research indicates leachate COD correlates significantly with TN and TP, possibly explaining higher COD in conventional systems. This study shows the integrated system reduced leachate COD compared to organic and conventional systems. Higher organic manure application in the organic system likely caused higher COD, though the conventional system also showed high COD despite minimal organic input, requiring further analysis.

Overall, organic systems reduced nitrogen leaching but increased phosphorus leaching compared to integrated and conventional systems. However, nitrogen leaching losses far exceeded phosphorus losses, and organic systems significantly improved soil total nitrogen, available phosphorus, and organic matter content. Therefore, organic systems help reduce nutrient leaching and improve soil fertility compared to integrated and conventional systems.

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