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An Integrated Strategy of Nitrogen Reduction, Microbial Amendment, and Straw Incorporation Mitigates Soil Degradation and Enhances Cucumber Yield in Northern Chinese Greenhouses

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Abstract

Facility agriculture is essential for modernizing the production of horticultural plants, while long-standing over-fertilization and improper tillage in some vegetable facilities in northern China have resulted in reduced soil quality, increased greenhouse gas (GHG) emissions, and diminished vegetable yields and quality. This study systematically analyzed the deteriorating health of typical cucumber facility soils in Hebei Province, China, induced by long-term over-fertilization. Based on field surveys, we explored dynamic changes in soil physicochemical properties across different durations of over-fertilization. Subsequently, a series of field trials were conducted to assess whether reducing nitrogen application, either alone or when combined with microbial agents, could ameliorate soil properties, reduce greenhouse gas emissions, and enhance cucumber productivity. The initial field assessment revealed severe topsoil salt and nutrient accumulation, with water-soluble salt content in 5-year-old greenhouses from Yongqing soaring to 3.82 $g \cdot kg^{-1}$, nearly eight times the level found in 1-year-old plots. Field experiments demonstrated that a 20% reduction in nitrogen application from the conventional rate of 900 $kg \cdot hm^{-2}$ effectively mitigated salt accumulation, improved the structure of the microbial community, and maintained cucumber yield at 66,914 $kg \cdot hm^{-2}$, an output comparable to conventional practices. More notably, integrating this 20% nitrogen reduction with an inoculation of *Bacillus megaterium* reduced the overall global warming potential by 26.7% and simultaneously increased cucumber yield to 72,747 $kg \cdot hm^{-2}$. The most comprehensive strategy combined deep tillage, soybean straw incorporation, and *B. megaterium* application under reduced nitrogen, which boosted nitrogen use efficiency by 13.7% and achieved the highest yield among all treatments. In conclusion, our findings demonstrate that a combined approach of nitrogen reduction, microbial amendment, and straw application offers an effective strategy to restore soil health, enhance crop productivity, and mitigate environmental impacts in protective vegetable production systems.

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Received: 31 August 2025
Revised: 18 October 2025
Accepted: 22 October 2025
Published: 25 October 2025

Citation: Yang, Y.; Guo, R.; Fu, X.; Sun, T.; Wang, Y.; Peng, Z. An Integrated Strategy of Nitrogen Reduction, Microbial Amendment, and Straw Incorporation Mitigates Soil Degradation and Enhances Cucumber Yield in Northern Chinese Greenhouses. *Agriculture* **2025**, *15*, 2231. https://doi.org/10.3390/agriculture15212231

Keywords: facility agriculture; reduced nitrogen fertilizer application; microbial community; soil quality; greenhouse gas emission

1. Introduction

As an important form of modern agriculture, protected vegetable production systems have achieved year-round, efficient production through artificial environmental control and has shown a trend toward large-scale and intelligent development worldwide [1]. With the intensification of population growth, frequent extreme weather events, and water shortages, facility agriculture has become one of the core means of ensuring agricultural supply due to its stress tolerance and high production efficiency [2]. The rise of vertical farming has further expanded production space, with over 500 commercial vertical farms established in East Asia and North America, achieving a 95% increase in water resource utilization efficiency through closed-loop systems [3]. By 2022, China's total horticultural facility area had exceeded 3.9 million hectares, accounting for over 80% of global facility agriculture land [4]. However, regional development imbalances remain prominent, with high adoption rates of smart greenhouses in eastern coastal regions, while western remote areas still face challenges such as weak infrastructure and lagging technological application. The highly intensive model of facility agriculture has also incurred significant environmental costs, with excessive fertilization being the core issue. Excessive fertilizer application is commonly practiced in China's agricultural facilities. Research shows that the average excess nitrogen fertilizer application per hectare reaches 33.26 kg, far exceeding the global average [5].

Excessive fertilization leads to the deterioration of soil physical and chemical properties, primarily manifested as secondary salinization and acidification [6], nutrient imbalance and disruption of the microbial community [7], and accumulation of harmful substances [8]. Facility coverings block rainwater leaching, causing salts to accumulate in the surface layer. A survey in the suburbs of Shenyang showed that 70.9% of greenhouse soils had a pH value below 6.5, with salt concentrations reaching 4–8 times those of open-field soils. Salt accumulation inhibits root water uptake, while increased hydrogen ion concentration activates toxic elements such as aluminum and manganese [9]. Excessive fertilization also leads to a concurrent decline in microbial activity, such as a 48% reduction in bacterial numbers and a 37% decrease in phosphatase activity in moderate degraded grassland soils, directly weakening nutrient transformation capacity [10]. In addition to soil quality degradation, excessive nitrogen fertilizer application significantly amplifies the greenhouse effect. Globally, 60% of N_2O emissions from farmland originate from nitrogen fertilizers, and the high temperature and humidity in greenhouse environments further catalyze this process [11]. Each kilogram of excess nitrogen fertilizer triggers 0.5–1.2 kg of CO_2 equivalent N_2O emissions, with a global warming potential 298 times that of CO_2 [11]. In China's greenhouse vegetable cultivation, nitrogen fertilizer loss rates from overapplication reach 30–50%, with nitrate leaching increasing by 4.2 times and ammonia volatilization rising by 3.8 times [12]. In wheat cultivation, the emission intensity under 180–190 $kg \cdot hm^{-1}$ of nitrogen fertilizer is 8.4 g $N_2O\text{-}N \cdot kg^{-1}$ of crop nitrogen uptake, but it surges to 26.8 g $N_2O\text{-}N \cdot kg^{-1}$ when the nitrogen application rate reaches 300 $kg \cdot hm^{-1}$ [11]. Excessive nitrogen fertilizer application also reduces fertilizer efficiency, prompting unplanned producers to apply more fertilizer, perpetuating a vicious cycle.

To address the aforementioned challenges, countries have explored potential solutions from diverse perspectives. For instance, farmers in the United States have promoted variable-rate fertilization equipment, which, when combined with soil sensing systems, optimizes fertilizer application rates by 15–40% [13]. In India, the use of neem oil-sprayed urea technology has been adopted to delay nitrogen release, resulting in increased yields of rice and wheat by 6.9–9.6% while reducing N_2O production [14]. In Japan, the promotion of "organic-inorganic composite fertilizers" as an alternative to pure fertilizers has seen the application of amino acid-coated urea in rice fields in Ibaraki Prefecture, maintaining yields unchanged while reducing nitrogen by 40% and increasing soil pH by 0.8 [15]. In Israel, 90% of recycled water is used for irrigation. Controlled-release fertilizers are applied through drip irrigation systems. In the Negev Desert, greenhouses use nitrogen and phosphorus-adsorbing resin to filter irrigation water, reducing nitrogen leaching in tomato cultivation by 76% and increasing productivity by 12% [16]. Brazil has developed and applied the FarmLab system, integrating satellite imagery with soil databases to provide dynamic fertilization plans for soybean farms, increasing nitrogen utilization efficiency to 68% [17]. The application of microbial agents in soil improvement in facilities has established multiple mature examples, with core mechanisms including nutrient conversion, pathogen suppression, pollution remediation, and structural optimization. In saline-alkali soil remediation, nitrogen-fixing bacteria *Azotobacter chroococcum* and phosphorus-solubilizing bacteria *Pseudomonas* spp. convert inert nitrogen gas into ammonium nitrogen and dissociate insoluble phosphorus, significantly reducing soil salinity and enhancing fertility [18]. However, soil compatibility must be considered for the successful application of microbial preparations. For example, *Sporosarcina pasteurii* is more effective in improving sandy soil than in clay soil because clay particles easily block the migration path of bacteria [19]. The combination of earthworm castings and wood ash in saline-alkali land can significantly enhance microbial activity, but the addition of zeolite has a weaker effect [20]. Therefore, the use of microorganisms needs to be optimized according to local conditions.

As the country with the largest area of agricultural facilities and the second-largest population, it is imperative for China to strike a balance between large-scale production and ecological conservation. Restoring agricultural facility soils degraded by excessive fertilizer application is an effective way to increase available arable land. However, there are differences in soil types across regions, and crop planting practices also vary. Therefore, it is necessary to propose targeted management solutions based on an investigation of the actual conditions of facility soils. In this context, strategies such as controlled nitrogen reduction, the application of microbial inoculants, adjustments in tillage depth, and the incorporation of crop straw have emerged as promising approaches to mitigate soil degradation and enhance sustainability. In this study, the health status of facility soils in Hebei Province, located in northern China, was investigated. A nitrogen fertilizer reduction scheme was proposed, combined with the use of microbial agents, straw incorporation, and deep plowing, to evaluate the effects of this scheme on soil nutrients, microbial communities, greenhouse gas emissions, as well as the yield of cucumbers cultivated in such soils. The study contributes to developing effective solutions for improving arable land availability and promoting ecological agriculture.

2. Materials and Methods

2.1. Study Site and Experimental Design

Field experiments were conducted in commercial plastic-roof greenhouses located in Qingyuan District (38°45′ N 115°29′ E), Suning County (38°25′ N 115°49′ E), Raoyang County (38°14′ N 115°43′ E), and Yongqing County (39°19′ N 116°29′ E) in Hebei Province, China. The region has a temperate continental monsoon climate with hot, humid summers and cold, dry winters. The mean annual temperature and precipitation are 12.0 °C and 550 mm in Qingyuan, 12.2 °C and 500 mm in Suning, 12.5 °C and 510 mm in Raoyang, and 11.5 °C and 540 mm in Yongqing, respectively. The soils in these experimental areas are classified as Stagnic Luvisols according to the World Reference Base for Soil Resources

(WRB, 2022) [21]. To establish a baseline for soil degradation patterns, an initial field assessment, involving soil sampling from 0 to 20 cm, 21–40 cm, 41–60 cm, 61–80 cm, 81–100 cm layers and laboratory analysis of physicochemical indices, assessed soil properties across greenhouses with different durations of use in these four locations. Three consecutive cucumber seasons (spring 2021–autumn 2023) were included in the study. A randomized complete block design with three replicates per treatment and individual plots of 23 m^2 was adopted. Building on the survey findings, the first set of experiments compared six nitrogen regimes to evaluate fertilizer reduction strategies: (1) conventional farmer rate (N1, 900 kg N hm^{-1}); (2) 20% reduction in that rate (N3, 720 kg N hm^{-1}); (3) N3 plus the nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) applied at 1% of the N rate; (4) N3 plus *Bacillus megaterium* inoculum at 180 kg hm^{-1} (N3MB); (5) N3 plus *Bacillus subtilis* inoculum (N3SB); and (6) N3 plus *Bacillus mucilaginosus* inoculum (N3IB). Next, to test the interaction with tillage, a second factorial trial was superimposed in 2022–2023: the six fertilizer regimes were combined with shallow tillage (12–15 cm) and deep tillage (50–60 cm). Urea (46% N), calcium superphosphate (12% P_2O_5) and potassium sulfate (50% K_2O) were broadcast and incorporated before transplanting to supply 40% of N and K and 100% of P; the remaining 60% of N and K were fertigated in three equal splits at early, peak, and late fruiting. Drip irrigation delivered 500 mm of water per season. Cucumber cv. ‘Shuoyuan Xianfeng 517’ was transplanted at 92 plants per plot. All other management followed local practice. Synergistic effects of tillage depth [shallow (S), deep (D)] and amendments (G1: nitrification inhibitor DMPP [22] + soybean straw; G2: DMPP + MB; G3: soybean straw + MB) were tested under 20% N reduction (CK).

2.2. Soil Sampling and Physicochemical Analyses

Fertilizer utilization rate (fertilizer production efficiency) is calculated as fruit yield divided by pure nitrogen application rate [23]. Soil samples were collected from 0 to 20 cm and 20–40 cm layers with an auger at early-, peak- and late-fruiting stages. Each plot provided three cores that were bulked, passed through a 2 mm sieve and split into three subsamples: one air-dried for chemical analyses, one kept at 4 °C for inorganic N extraction within 48 h, and one frozen at −80 °C for DNA extraction. Soil pH and electrical conductivity (EC) were measured in 1:2.5 and 1:5 soil-to-water suspensions, respectively, using a pH/conductivity meter (LC-MP-31) [24]. Soil organic carbon (SOC) was determined by the dichromate oxidation method. And total nitrogen (TN) was digested with concentrated H_2SO_4 and analyzed using a continuous-flow auto analyzer (SmartChem 200, AMS Alliance, Guidonia, Italy) [25]. Ammonium nitrogen (NH_4^+–N) and nitrate nitrogen (NO_3^-–N) were extracted with 2 M KCl and analyzed using a continuous-flow auto analyzer (SmartChem 200) [24]. Available phosphorus (AP) was extracted with 0.5 M $NaHCO_3$ and determined colorimetrically using a UV–Vis spectrophotometer (UV-1100) [26], whereas available potassium (AK) was extracted with 1 M NH_4OAc and quantified by a flame photometer (FP6400, Youke Instrument, Shanghai, China) [27]. Water-stable aggregates were separated at harvest from 0 to 20 cm soil samples using a soil aggregate analyzer (TPF-100, Zhejiang Top Cloud-agri Technology, Hangzhou, China) through wet sieving into >2 mm, 0.25–2 mm, 0.053–0.25 mm, and <0.053 mm fractions. Aggregates retained on each sieve were oven-dried at 75 °C to a constant weight, and the proportion of each size fraction was calculated based on dry mass [28].

2.3. Microbial Community Profiling

Microbial DNA was extracted from 0–20 cm soil collected during the late fruiting stage, using the E.Z.N.A. Soil DNA Kit. The V3-V4 region of the bacterial 16S rRNA gene was amplified with primers 338F (5′-ACTCCTACGGGAGGCAGCA-3′) and 806R (5′-

GGACTACHVGGGTWTCTAAT-3′); the fungal ITS-1 region was amplified with ITS5F (5′-GGAAGTAAAAGTCGTAACAAGG-3′) and ITS1R (5′-GCTGCGTTCTTCATCGATGC-3′). PCR products were purified, pooled and sequenced on the Illumina MiSeq platform [29]. Alpha diversity indices were calculated from OTU tables rarefied to the minimum sequence number.

2.4. Greenhouse Gas Measurements

Fluxes of N_2O, CO_2 and CH_4 were measured using static opaque chambers (PVC, internal diameter 21 cm, height 12 cm) inserted 2 cm into the soil between plant rows. Three chambers per plot were sealed for 40 min and 20 mL headspace samples were withdrawn at 0, 20 and 40 min with polypropylene syringes. Fluxes were calculated from the linear change in concentration, corrected for chamber temperature and pressure. Sampling campaigns were conducted every 5–7 days throughout the season, with additional measurements within 48 h after each fertilization or irrigation event. Cumulative seasonal emissions were obtained by trapezoidal integration of daily fluxes [30]. The global warming potential (GWP) of each greenhouse gas was calculated to express total emissions in CO_2-equivalent (CO_2-eq) units. GWP factors of 1 for CO_2, 28 for CH_4, and 265 for N_2O were adopted from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report [31]. Accordingly, the total GWP was calculated as follows:

$$\text{GWP} = \text{Total } CO_2 \text{ emission} + 28 \times \text{Total } CH_4 \text{ emission} + 265 \times \text{Total } N_2O \text{ emission}$$

where total emissions were expressed as kg CO_2-eq·hm^{-2}·season^{-1}.

2.5. Plant Sampling and Analyses

At final harvest, 30 representative plants per plot were fixed at 105 °C for 30 min, then oven-dried at 75 °C to constant weight. Total nitrogen (N), phosphorus (P), and potassium (K) in plant tissues were determined after digestion with concentrated H_2SO_4–H_2O_2. Nitrogen was measured using a continuous-flow auto analyzer (SmartChem 200), phosphorus was determined colorimetrically by the vanadium–molybdate yellow method with a UV–Vis spectrophotometer (UV-1100), and potassium was quantified by flame photometry (FP6400) [24].

2.6. Statistical Analyses

This study set the conventional nitrogen application rate (900 kg·hm^{-2}, denoted as N1) as the control and established integrated management treatments based on a 20% nitrogen reduction (720 kg·hm^{-2}, denoted as N3); these treatments incorporated three *Bacillus* inoculants (*Bacillus megaterium*, *Bacillus subtilis*, *Bacillus mucilaginosus*), two tillage depths (shallow tillage at 12–15 cm, deep tillage at 50–60 cm), and soybean straw incorporation. For each treatment, the study measured soil physicochemical properties (ammonium nitrogen, nitrate nitrogen, available phosphorus, water-soluble salts, etc.), soil bacterial/fungal community composition, greenhouse gas (N_2O, CO_2) emissions, as well as cucumber growth traits (single fruit weight, yield) and nitrogen use efficiency.

Treatment effects were evaluated by one-way and two-way ANOVA using IBM SPSS Statistics 20.0. The two-way ANOVA considered tillage practices (T) and integrated fertilizer management (G) as fixed factors, and their interaction (T × G) was also tested. Multiple comparisons among means were performed using Duncan's multiple range test at $p \leq 0.05$.

3. Results

3.1. Excessive Fertilization Drives Pronounced Salt and Nutrient Buildup in Topsoil of Hebei Greenhouse Vegetable Fields

Recent years have seen a sustained increase in the total consumption of fresh vegetables. Increasing nitrogen fertilizer application rates in protected-culture vegetable fields is considered an effective short-term measure to boost protected-culture vegetable yields. Hebei Province is an important production area for greenhouse cucumbers in northern China, where the issue of excessive fertilizer application is particularly severe. To clarify the impact of continuous excessive fertilizer application on greenhouse vegetable field soils, we investigated soil properties in Qingyuan, Suning, Raoyang, and Yongqing, four major greenhouse vegetable production areas in Hebei Province, as part of the initial field assessment. In general, the organic nitrogen, total nitrogen, NH_4^+-N, NO_3^--N, available phosphorus, and available potassium in the soils of the four regions we investigated were mainly found in the 0–20 cm soil layer, and their content gradually decreased as the soil depth increased.

Water-soluble salt content in the 0–20 cm layer increased sharply in plots with longer cultivation duration in Yongqing and Suning (Figure 1a). Yongqing's water-soluble salt content rose from 0.5 g·kg^{-1} in 1-year plots to 3.82 g·kg^{-1} in 5-year plots, followed by a partial decline in 10+ year plots. Suning also showed a dramatic rise from 1.03 g·kg^{-1} in 1-year plots to 2.20 g·kg^{-1} in 5-year plots, whereas Qingyuan and Raoyang exhibited modest fluctuations. Across the four regions, organic matter in the 0–20 cm layer increased with longer land use durations (Figure 1b), with Suning exhibiting the most substantial rise from 1 year to 10+ years (142.3%), followed by Yongqing (91.1%), Qingyuan (78.2%), and Raoyang (52.6%). Total nitrogen in the 0–20 cm layer increased with longer land use durations across all regions (Figure 1c). Suning demonstrated the highest gain, rising from 0.59 g·kg^{-1} in 1-year plots to 1.75 g·kg^{-1} in 10-year plots, a 196.6% increase; Yongqing showed a rise from 0.40 g·kg^{-1} to 1.15 g·kg^{-1}, a 187.5% increase, Qingyuan showed a rise from 0.89 g·kg^{-1} to 2.21 g·kg^{-1}, a 132.0% increase, while Raoyang exhibited a relatively moderate growth of 40%. NH_4^+-N levels in the 0–20 cm layer rose sharply in Suning, increasing from 1.74 mg·kg^{-1} in 1-year plots to 5.88 mg·kg^{-1} in 10+ year plots (Figure 1d). Qingyuan and Yongqing showed steady but less dramatic gains, with Qingyuan's values rising from 5.22 mg·kg^{-1} to 7.59 mg·kg^{-1} and Yongqing from 4.22 mg·kg^{-1} to 5.47 mg·kg^{-1}. NO_3^--N concentrations in the 0–20 cm layer escalated most prominently in Qingyuan and Raoyang as land use duration extended. Yongqing exhibited only a modest 8.8% increase, while Suning showed a rise of 46.0% (Figure 1e). Available phosphorus in the 0–20 cm layer escalated dramatically in Suning and Yongqing (Figure 1f). Suning's available phosphorus surged from 37.4 mg·kg^{-1} in 1-year plots to 254.2 mg·kg^{-1} in 10+ year plots, showing a 579.7% increase, while Yongqing's available phosphorus rose from 26.4 mg·kg^{-1} to 174.3 mg·kg^{-1}. Qingyuan and Raoyang showed more moderate gains. Available potassium in the 0–20 cm layer increased most strikingly in Suning (Figure 1g), rising from 122.4 mg·kg^{-1} in 1-year plots to 638.5 mg·kg^{-1} in 10+ year plots. Raoyang and Yongqing also showed significant gains. Although soil pH varies across different regions as the number of years of service increases, we have yet to discover a pattern (Figure 1h). Our research findings clearly illustrate the evolution from problem to solution: long-term excessive fertilization has led to soil degradation, including salinization, nutrient imbalance, and microbial dysregulation, thereby exacerbating environmental costs such as increased greenhouse gas emissions. By implementing a combination of measures—including a 20% reduction in nitrogen fertilizer application, inoculation with the B. megaterium strain, deep plowing, and straw return to the field—we successfully reversed these trends. This strategy simultaneously improved soil structure and microbial communities, enhanced nutrient use efficiency, reduced greenhouse gas emissions, and achieved the highest yields, thereby providing a comprehensive solution for sustainable intensive agriculture in protected cropping systems.

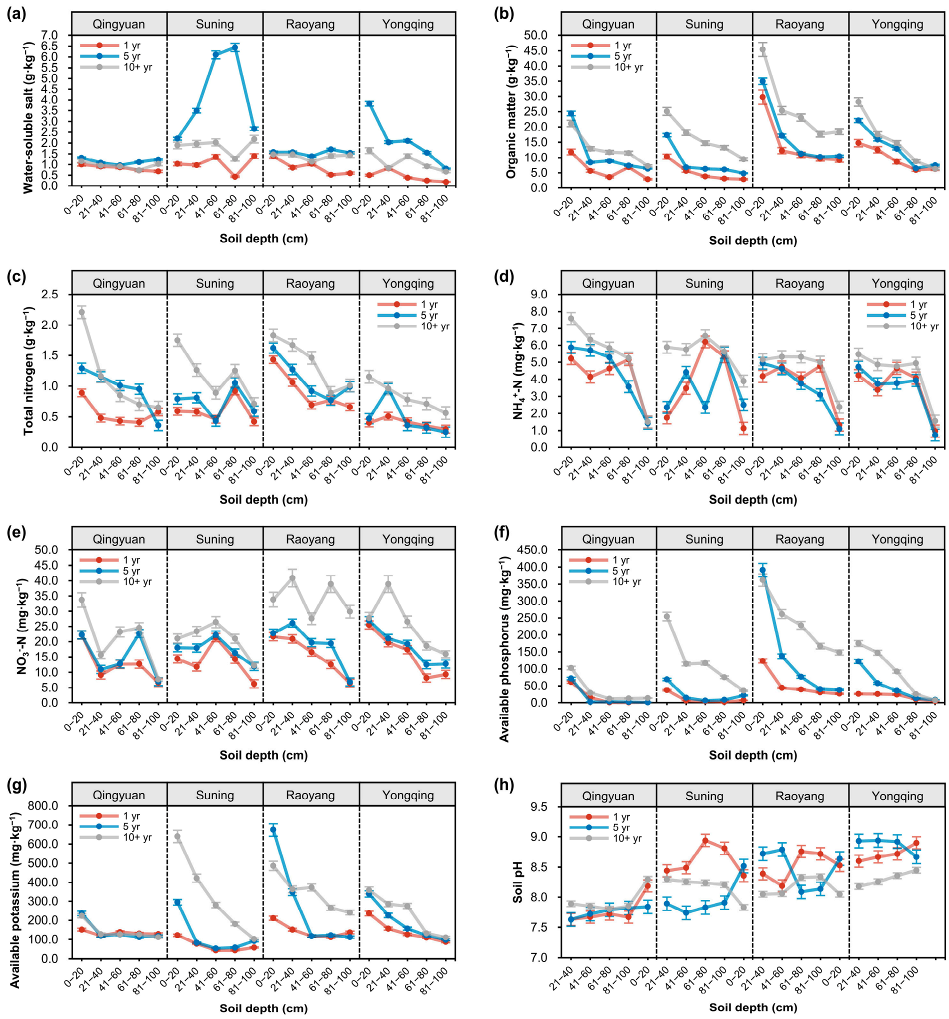

Figure 1. Soil properties across different ages of service in the main cultivation areas of greenhouse cucumbers in Hebei. (**a**) Water-soluble salts, (**b**) Soil organic matter, (**c**) Total nitrogen, (**d**) NH_4^+-nitrogen, (**e**) NO_3^--nitrogen, (**f**) Available phosphorus, (**g**) Available potassium, (**h**) Soil pH. Values represent means ± SD of three replicates.

3.2. Sustained Cucumber Yield Achieved with 20% Nitrogen Reduction Through Improved Soil and Microbial Conditions

As a remedy for excessive nitrogen fertilizer application, we conducted field trials to test different levels of nitrogen fertilizer reduction. A previous report by Guo et al. showed that moderate nitrogen reduction (20–30%) in greenhouse cucumber farming not only maintained or increased yield but also reduced soil nitrogen leaching and residual nitrogen, with the 20% reduction treatment showing the most balanced improvement in fruit quality and nitrogen use efficiency [32]. Here, we found that reducing nitrogen fertilizer application by 20% (N3 treatment) based on the farmers' usual application rate (900 kg·hm^{-2}) effectively alleviated water-soluble salt accumulation (Figure 2a). Compared with N1, a 20% reduction in nitrogen fertilizer application did not significantly alter the Shannon index or Chao1 index of soil bacteria and fungi, indicating that nitrogen reduction level had no substantial impact on the overall diversity and species richness of the soil bacterial and fungal communities (Figure A1). Furthermore, the relative abundance of the *Actinobacteriota*, *Firmicutes*, and *Basidiomycota* phyla rose and the relative abundance of the *Acidobacteriota*, *Bacteroidota*, and *Chytridiomycota* phyla decreased (Figure 2b,c). In addition, the analysis of the soil microbial community indicated that the most prevalent bacterial classes were *Gammaproteobacteria* and *Alphaproteobacteria*, which collectively constituted approximately 25% of the total community (Figure A2a). A substantial decrease in *Gammaproteobacteria* was observed under N1, N3, N4, and N5 treatments in comparison to CK, while a significant decrease in *Alphaproteobacteria* was noted in N1 and N5. A significant decline in *Bacteroidia* was observed in N1, N3, and N5. The *Vicicamibacteria* were found to be significantly enriched in sample N1, while the *Blastocatellia* and *Acidobacteriae* were more prevalent in N1, N4, and N5. *Actinobacteria* demonstrated a significant increase under N3, which also exhibited the lowest *Verrucomicrobiae* abundance. Among the various classes of fungi, *Sordariomycetes* exhibited the most prevalent class, with an average abundance exceeding 30%, and a significantly higher prevalence in N4 and N5 (Figure A2b). The *Dothideomycetes* and *Mortierellomycetes* were found to be more prevalent in the N2, N5, and CK treatments. The population of *Spizellomycetes* exhibited an increase in N1, N2, and N5, with the most significant increase observed in N1. *Agaricomycetes* and *Pezizomycetes* were found to be significantly enriched only in N3. These results indicate that nitrogen reduction treatments significantly altered the structure of both bacterial and fungal communities.

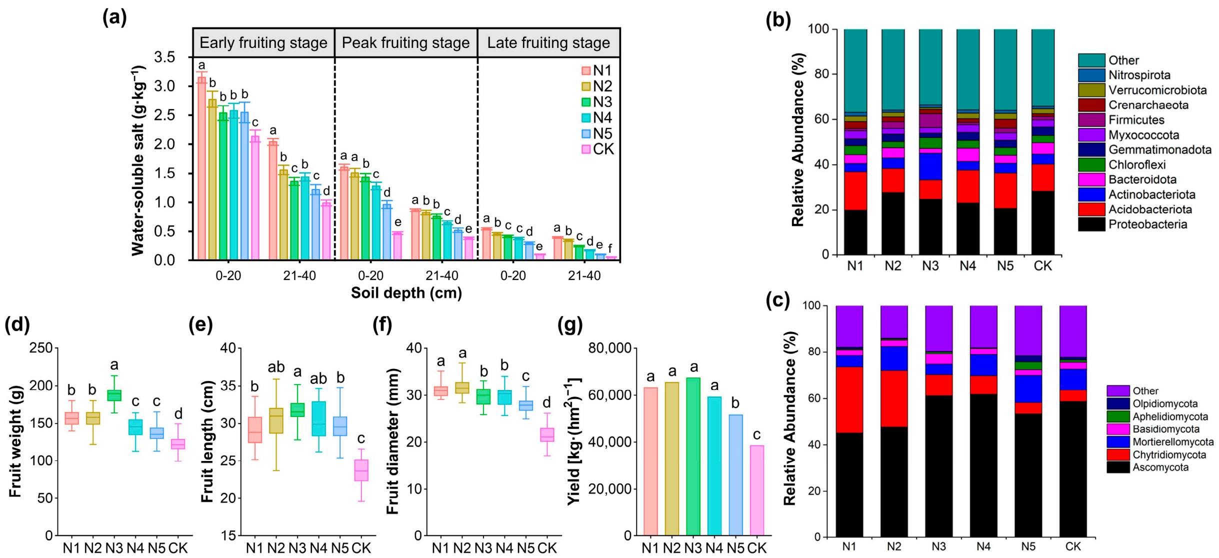

Figure 2. Impact of nitrogen fertilizer reduction on soil salinity, microbial community composition, and greenhouse cucumber. (**a**) Impact of nitrogen reduction treatment on the content of water-soluble salts in the soil of greenhouse cucumber fields. Customary nitrogen fertilizer application (N1), conventional nitrogen fertilizer application with a 10% reduction (N2), a 20% reduction (N3), a 30% reduction (N4), a 50% reduction (N5), and no nitrogen fertilizer (CK) treatments were applied. Soil water-soluble salt content was measured at the early fruiting stage, peak fruiting stage, and late fruiting stage of cucumbers. Values represent means ± SD of three replicates. Effect of reduced nitrogen fertilizer application on the relative abundance of bacteria (**b**) and fungi (**c**) evaluated at phylum level. Effect of nitrogen reduction on cucumber fruit weight (**d**), fruit length (**e**), and fruit diameter (**f**). Box plots represent the data distribution, and the internal lines represent the median. (**g**) Mean cucumber yield under different treatments. Statistical significance was assessed by one-way ANOVA followed by Duncan's test. Different lowercase letters denote significant differences ($p < 0.05$) between groups, while shared letters indicate no significant difference.

The above-mentioned improvement effects directly promoted the increase in cucumber fruit weight (Figure 2d) and fruit length (Figure 2e), but not fruit diameter (Figure 2f). Compared with customary fertilization (N1), reducing nitrogen fertilizer application by 10% (N2) and 20% (N3) slightly increased yield, but not significantly (Figure 2g). The N3 treatment yielded 66,914 kg·hm^{-2}, which was not significantly different from the customary fertilization (N1) but significantly higher than the 50% nitrogen reduction treatment (N5). In summary, we found that reducing nitrogen fertilizer application by 20% based on customary current fertilization levels is an effective measure to restore soil microbial communities and improve cucumber yield and quality while maintaining soil nutrient levels.

3.3. Applying Bacillus Inoculants with 20% Less Nitrogen Enhances Soil Fertility, Reshapes Microbial Communities, Lowers GWP, and Boosts Cucumber Production

Bacillus preparations have been increasingly recognized for their potential in controlling soil-borne diseases in recent years [33], but there has been little research on their combined use with fertilizer reduction measures to restore soil fertility. We studied the effects of these treatments on soil nutrients and microbial communities by applying microbial agents: *Bacillus megaterium* (MB), *Bacillus subtilis* (SB), and *Bacillus mucilaginosus* (IB), on the basis of a 20% reduction in nitrogen fertilizer (N3). MB generally reduced NH_4^+-nitrogen in the early and late fruiting stages (Figure 3a), with a maximum decrease of 2.37 mg·kg^{-1} in the 21–40 cm soil layer, and only a slight increase in the shallow layer during the peak fruiting stage. SB reduced NH_4^+-N in the early fruiting stage, but significantly increased it in the peak and late fruiting stages. IB reduced it in the shallow layer in the early fruiting stage but increased it in the deep layer, and increased it in both the peak and late fruiting stages. MB significantly reduced NO_3^--N in the early and peak fruiting stages (the maximum decrease in the 21–40 cm soil layer was 14.25 mg·kg^{-1}), but increased slightly in the late fruiting stage (Figure 3b). SB significantly reduced NO_3-N in the early fruiting stage in the shallow layer but increased in the deep layer, and increased significantly in both the peak and late fruiting stages. IB reduced nitrate nitrogen in the early fruiting stage, increased in the shallow layer but decreased in the deep layer in the peak fruiting stage, and increased significantly in the late fruiting stage. The microbial effects showed strain, growth stage, and soil layer specificity. SB and IB generally increased nitrogen during the peak late fruiting stage, while MB mostly showed a decrease, which may have been caused by enhancing the absorption of nitrogen from the soil by plants. *Bacillus* inoculants significantly changed the bacterial (Figure 3c) and fungal (Figure 3d) communities, with increased relative abundances of the *Acidobacteria*, *Bacteroidetes*, *Ascomycota* and *Mortierellomycota* phyla and decreased abundances of the *Actinobacteria*, *Firmicutes*, and *Chytridiomycota* phyla. Soil bacterial communities at the class level exhibited a predominance of *Gammaproteobacteria* and *Alphaproteobacteria*, constituting an aggregate percentage of 20–30% (Figure A3a). A decline in *Gammaproteobacteria* was observed in N3SB and CK in comparison to N3 and N3MB, while *Alphaproteobacteria* exhibited a decrease in N3 and N3SB relative to N1 and N3MB. *Bacteroidia* exhibited a decline across all treatment groups relative to CK. The *Vicicamibacteria* exhibited the highest levels of abundance in N1, while the *Blastocatellia* demonstrated the lowest levels of abundance outside of N1. The population of *Actinobacteria* exhibited an increase in both N3 and N3MB. *Acidobacteriae* exhibited an increase in all treatments in comparison to CK and N1. For the fungi, the *Sordariomycetes* (25–47%) exhibited the most significant increase in N3MB (+73.35%) (Figure A3b). Furthermore, *Mortierellomycetes* exhibited a substantial increase in abundance in N3MB, N3IB, and N3SB. *Agaricomycetes* exhibited a decline exclusively in N3SB, while *Pezizomycetes* demonstrated a pronounced decrease across all amended treatments.

In addition, the N3IB and N3SB treatments significantly reduced the cumulative emissions of N_2O and CO_2, with a decrease in the global warming potential (GWP) of 26.71% and 16.26%, respectively (Table 1). As compared with N3, N3MB significantly improved all parameters, including fruit weight (Figure 3e), fruit length (Figure 3f), fruit diameter (Figure 3g), and yield (Figure 3h), which reached 72,747 kg·hm^{-2}; there was no significant difference between SB treatment and N3 in terms of all parameters, and the yield increased slightly; the weight of a single melon in IB treatment significantly increased to 211.07 g, but there was no significant increase in fruit length, fruit diameter, and yield as compared with N3. Overall, MB was the only inoculum that comprehensively optimized fruit morphology and yield. These results showed the potential of reducing nitrogen by 20% and applying *Bacillus megaterium* to improve soil quality in protected vegetable fields, enhance cucumber yield and reduce greenhouse gas emissions.

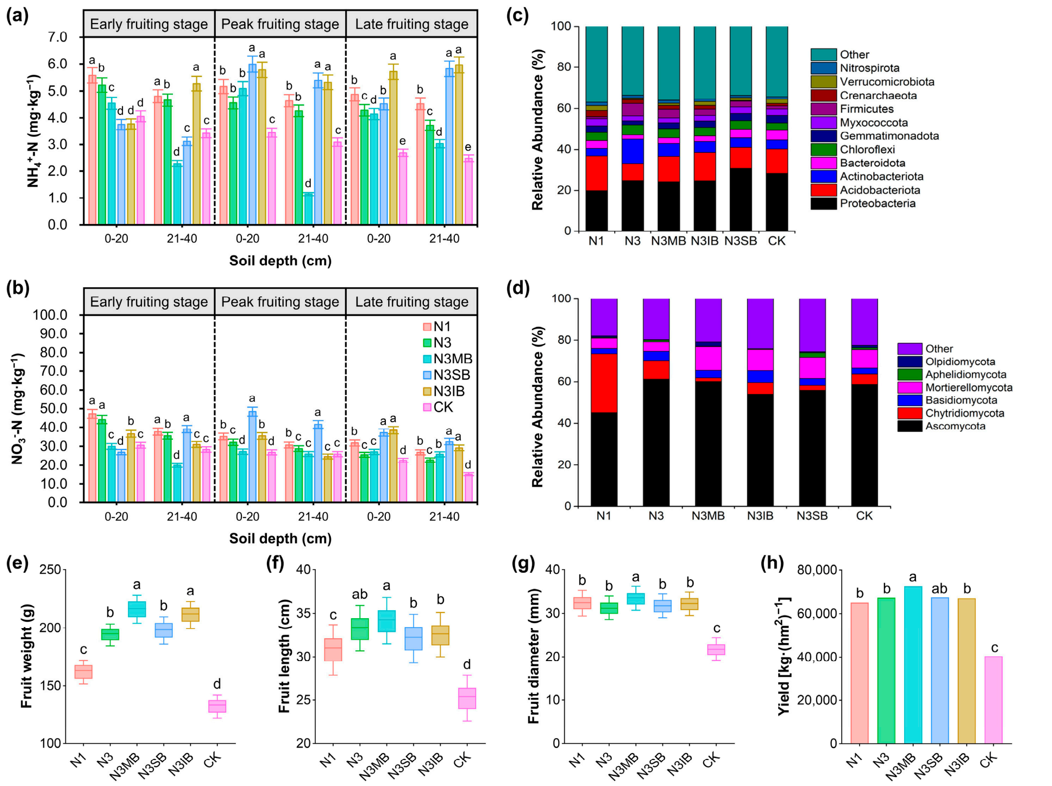

Figure 3. Impact of *Bacillus* inoculants on soil nitrogen, microbial community composition, and greenhouse cucumber. Impact of *Bacillus megaterium* (MB), *Bacillus subtilis* (SB), and *Bacillus mucilaginosus* (IB) inoculants treatment on the content of NH_4^+-nitrogen (**a**) and NO_3^--nitrogen (**b**) content in the soil of greenhouse cucumber fields, measured at the early fruiting stage, peak fruiting stage, and late fruiting stage of cucumbers. Values represent means ± SD of three replicates. Effect of reduced *Bacillus* inoculants on the relative abundance of bacteria (**c**) and fungi (**d**) evaluated at phylum level. Effect of nitrogen reduction on cucumber fruit weight (**e**), fruit length (**f**), and fruit diameter (**g**). Box plots represent the data distribution, and the internal lines represent the median. (**h**) Mean cucumber yield under different treatments. Statistical significance was assessed by one-way ANOVA followed by Duncan's test. Different lowercase letters denote significant differences ($p < 0.05$) between groups, while shared letters indicate no significant difference.

Table 1. Impact of *Bacillus* inoculants on soil global warming potential.

Treatment	N_2O GWP	CO_2 GWP	CH_4 GWP	Total GWP
N3	128.46 ^{a}	5185.51 ^{a}	−10.41 ^{c}	5303.56 ^{a}
N3IB	76.85 ^{c}	3816.00 ^{c}	−5.78 ^{a}	3887.07 ^{c}
N3SB	100.17 ^{b}	4348.80 ^{b}	−7.73 ^{b}	4441.24 ^{b}
N3MB	125.34 ^{a}	5123.15 ^{a}	−10.74 ^{c}	5237.75 ^{a}

Statistical significance was assessed by one-way ANOVA followed by Duncan's test. Different lowercase letters denote significant differences ($p < 0.05$) between groups, while shared letters indicate no significant difference.

3.4. Optimal Soil Remediation and Crop Performance Achieved via Deep Tillage Implementing 20% N Reduction, *B. megaterium* Inoculation, and Soybean Straw Application

Straw retention is an effective measure to prevent air pollution caused by the burning of crop residues [34]. The selection of straw may have certain differences in terms of improving facility vegetable fields. After determining the benefits of nitrogen reduction and microbial inoculants, we focused on further optimizing the best cultivation method for this integrated treatment and evaluated the benefits of applying straw based on this method.

Soil physical properties are the foundation of soil health, directly determining the migration of water, air, and nutrients in the soil and the growth environment of root systems. During the late fruiting stage, we analyzed the composition of soil aggregates in the 0–20 cm soil layer, and found that soil aggregation improved with the application of amendments across tillage practices (Figure 4a). Under shallow tillage, all treatments (SG1, SG2, and SG3) reduced powdery particles (<0.053 mm) while increasing the proportion of micro-aggregates, though only SG3 maintained levels of macro-aggregates (>2 mm) comparable to the control. Amendments under deep tillage (DG1, DG2, and DG3) universally increased small aggregates (0.25–2 mm) and micro-aggregates (0.25–0.053 mm) while decreasing powder particles. DG1 was unique in that it preserved macro aggregates. Also, in the peak fruiting stage, we evaluated the nitrogen dynamics, and found pronounced treatment effects (Figure 4b,c). DG3 exhibited the most favorable profile, with substantially elevated NH_4^+-N retention in subsoil layers alongside consistently reduced nitrate-N accumulation throughout the soil profile. This pattern—contrasting with the NO_3^--N surpluses observed in treatments like SG2 and the limited nitrogen preservation in controls, suggests DG3 optimized nitrogen availability during high demand, minimizing leaching risks while maintaining subsurface reserves.

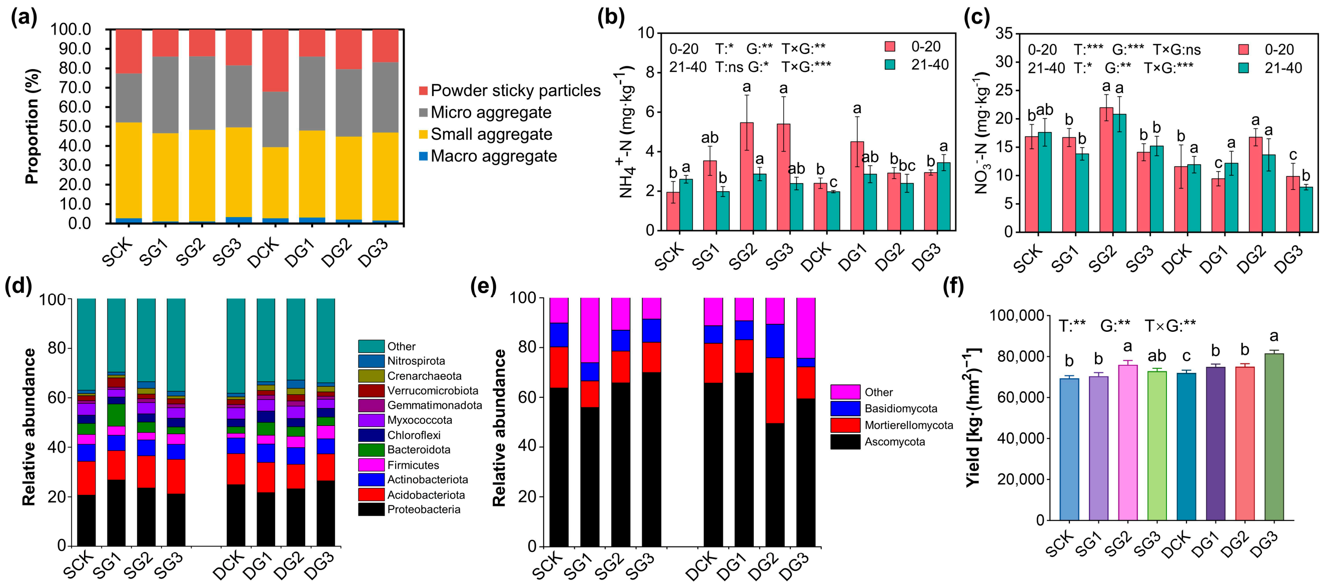

Figure 4. Impact of integrated fertilizer management on soil particle properties, nitrogen, microbial community composition, and cucumber yield. Effect of different tillage and fertilization control methods on soil aggregate distribution (**a**), on the content of NH_4^+-nitrogen (**b**), the NO_3^--nitrogen (**c**), and on the relative abundance of bacteria (**d**) and fungi (**e**) evaluated at phylum level. (**f**) Mean cucumber yield under different treatments. Statistical significance was assessed by one-way ANOVA and two-way ANOVA followed by Duncan's test. T, different tillage practices; G, different integrated fertilizer managements; T × G, interaction between tillage and fertilizer management. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ns $p > 0.05$. Different lowercase letters denote significant differences ($p < 0.05$) between groups, while shared letters indicate no significant difference.

We further analyzed the effects of these treatments on the soil microbial community. Bacterial and fungal community analysis revealed that shallow and deep tillage treatments significantly altered phylum-level composition compared to the control (Figure 4d). SG1 treatment exhibited notably higher *Proteobacteria*, *Verrucomicrobiota* and *Bacterodota* but lower *Myxococcota* relative abundance than other SG treatments, while SG3 showed elevated *Acidobacteria*. Deep tillage treatments displayed distinct patterns: DG1 reduced *Proteobacteria* but increased *Bacteroidata*, and *Chloroflexi*, relative to DCK, whereas DG3 exhibited the highest *Firmicutes* and *Proteobacteria*. Fungal phylum-level responses to tillage depth were also distinct (Figure 4e). Shallow tillage decreased *Ascomycota* in SG1 but increased it in SG3 compared to SCK, while *Basidiomycota* and *Mortierellomycota* declined across all SG treatments relative to SCK. Deep tillage further modulated fungal communities: DG2 reduced *Ascomycota* and increased *Mortierellomycota* compared to DCK, and showing elevated *Basidiomycota*. DG3 exhibits lowest relative abundance of *Basidiomycota*.

Compared to shallow tillage and control treatments, deep tillage significantly increased crop yields, with DG3 demonstrating the highest productivity among all treatments (Figure 4f). In addition, we found that these integrated fertilizer managements enhanced fertilizer use efficiency across nutrient types, with SG2 and DG3 demonstrating particularly pronounced improvements (Table 2). Under shallow tillage, SG2 elevated nitrogen, phosphorus, and potassium efficiency to peak levels, while under deep tillage, DG3 achieved the highest gains, significantly outperforming both controls and other amendments. Integrated fertilizer managements significantly reduced global warming potential, with SG2 and DG3 demonstrating the most pronounced mitigation effects under shallow and deep tillage, respectively (Table 3). SG2 lowered total GWP primarily through N_2O and CO_2 emissions reduction, while DG3 achieved the lowest overall GWP via coordinated suppression of all major greenhouse gases. In summary, we found that reducing nitrogen fertilizer application by 20% through deep plowing and combining it with soybean straw and MB can optimize yield, soil restoration, and greenhouse gas control, providing an effective solution for soil restoration in agricultural facilities that have been over-fertilized for years.

Table 2. Effect of different tillage and fertilization control managements on fertilizer use efficiency.

Management	Fertilizer Use Efficiency - Nitrogen	Fertilizer Use Efficiency - Phosphorus	Fertilizer Use Efficiency - Potassium
SCK	96.76 ^{b}	154.81 ^{b}	58.05 ^{b}
SG1	98.14 ^{b}	157.02 ^{b}	58.88 ^{b}
SG2	106.30 ^{a}	170.08 ^{a}	63.78 ^{a}
SG3	102.02 ^{ab}	163.23 ^{ab}	61.21 ^{ab}
DCK	100.20 ^{c}	160.33 ^{c}	60.12 ^{c}
DG1	104.86 ^{b}	167.77 ^{b}	62.91 ^{b}
DG2	105.12 ^{b}	168.19 ^{b}	63.07 ^{b}
DG3	113.69 ^{a}	181.91 ^{a}	68.22 ^{a}
Significance			
T	**	**	***
G	**	***	***
T × G	*	*	**

Statistical significance was assessed by one-way ANOVA followed by Duncan's test. Different lowercase letters denote significant differences ($p < 0.05$) between groups, while shared letters indicate no significant difference. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

Table 3. Soil global warming potential under different tillage and fertilization control managements.

Management	N_2O GWP	CO_2 GWP	CH_4 GWP	Total GWP
SCK	1435.09 ^{a}	6323.32 ^{a}	−16.66 ^{c}	7741.74 ^{a}
SG1	1059.85 ^{b}	5331.99 ^{ab}	−13.49 ^{bc}	6378.35 ^{ab}
SG2	800.90 ^{c}	3803.96 ^{c}	−6.95 ^{a}	4597.91 ^{c}
SG3	978.19 ^{b}	5203.47 ^{b}	−11.32 ^{b}	6170.35 ^{b}
DCK	1024.08 ^{a}	4525.70 ^{ab}	−12.97 ^{b}	5536.81 ^{a}
DG1	869.02 ^{ab}	3816.21 ^{b}	−8.41 ^{a}	4676.82 ^{b}
DG2	786.77 ^{bc}	4039.84 ^{b}	−7.48 ^{a}	4819.12 ^{ab}
DG3	678.96 ^{c}	3722.48 ^{b}	−5.91 ^{a}	4395.53 ^{b}
Significance				
T	***	***	**	**
G	***	***	**	**
T × G	*	**	*	*

Statistical significance was assessed by one-way ANOVA followed by Duncan's test. Different lowercase letters denote significant differences ($p < 0.05$) between groups, while shared letters indicate no significant difference. *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$.

4. Discussion

The excessive application of nitrogen fertilizers poses a threat to the sustainable supply of agricultural products by causing damage to facility soil [6,7]. This study investigated a soil amendment strategy combining reduced nitrogen fertilizer application with the use of microbial inoculants, aiming to improve soil quality in northern China's agricultural facilities. The results indicate that long-term excessive application of nitrogen fertilizer has led to severe soil degradation in greenhouse cucumber fields, characterized by an increase in water-soluble salt content, which reached 230% in Yongqing, and significant accumulation of total nitrogen, ammonium nitrogen, nitrate nitrogen, available phosphorus, and available potassium (compared to one-year-old cultivated soil) in the 0–20 cm soil layer. These changes have triggered disruptions in soil microbial communities, and increased greenhouse gas emissions (such as N_2O and CO_2). By reducing nitrogen fertilizer application rates by 20% from the conventional 900 kg·hm^{-2} (N3 treatment), we observed a mitigation of water-soluble salt content, increased abundance of the *Acidobacteria* and *Bacteroidetes* phyla, and decreased abundance of the *Actinobacteria* phylum. The cucumber yield under this treatment reached 66,914 kg·hm^{-2}, which was comparable to that under conventional fertilization (N1) but significantly higher than that under 50% nitrogen reduction treatment (N5), indicating that moderate nitrogen reduction can improve soil health while maintaining yield.

The combination of a 20% reduction in nitrogen fertilizer application and the use of *Bacillus* microbial inoculants (particularly *Bacillus megaterium*, N3MB treatment) significantly improved soil fertility, specifically reflected in increased fruit length and diameter, as well as yield. The microbial community structure was optimized, with an increase in beneficial bacteria and a decrease in harmful bacteria. Additionally, this treatment significantly reduced the cumulative emissions of N_2O and CO_2, with a 26.71% reduction in global warming potential (GWP). The optimal strategy (DG3), which combined deep plowing, a 20% reduction in nitrogen fertilizer, Bacillus megaterium inoculation, and soybean straw application, delivered the most comprehensive benefits, as clearly evidenced in our findings. This approach significantly improved soil structure (Figure 4a). It also dramatically enhanced nutrient availability, driving the highest nitrogen use efficiency of 113.69% and culminating in the peak cucumber yield of all treatments (Figure 4f). Furthermore, this integrated method resulted in the lowest overall global warming potential, successfully curbing emissions of all major greenhouse gases and underscoring its dual advantage for both productivity and environmental sustainability.

Building on existing research into soil improvement and nitrogen fertilizer management in protected vegetable production, this study further broadens the scope of knowledge in this field. Previous studies have shown that high nitrogen inputs can lead to soil acidification and a decline in microbial functional diversity. For example, Wang et al. found that high nitrogen application (1002 kg N hm^{-2} $year^{-1}$) resulted in soil acidification and reduced microbial activity [35]. Similarly, Wang et al. reported that excessive nitrogen fertilizer altered microbial community structure and function [36]. In contrast, this study reversed these negative effects by moderately reducing nitrogen fertilizer and combining microbial inoculants and organic matter, thereby improving soil conditions and crop yields. Additionally, the role of *Bacillus* spp. in improving soil health and plant growth through nutrient solubilization and disease suppression has been confirmed [18]. This study observed that *Bacillus* inoculation increased nutrient availability and cucumber yield, consistent with these findings. The application of soybean straw further enhanced soil organic matter and provided a substrate for microbial activity, aligning with the benefits of organic amendments [37]. Furthermore, unlike Kim et al., who found yield stability only in high-nutrient soils under N reduction [38], we demonstrate yield resilience across typical Hebei soils, highlighting region-specific adaptability.

Soil aggregates are the cornerstone of soil structure, and their stability is closely related to soil erosion resistance and fertility. Numerous studies have shown that traditional frequent tillage, especially shallow tillage such as rotary tillage, destroys large aggregates in the topsoil and reduces their stability [39]. Conservation tillage (such as no-till or reduced-till) can increase soil organic carbon, thereby improving aggregate stability [40]. Deep tillage, as an alternative tillage method, has more complex effects. Research has shown that deep plowing combined with straw incorporation can significantly improve soil aggregate stability, increase the activity of certain enzymes, and increase the number of soil microorganisms [41,42].

The decomposition process of straw, a loose organic material, produces humus that promotes the formation of soil aggregates, thereby improving soil structure, reducing bulk density, and increasing porosity. This is particularly important for the soil in facility vegetable gardens, which is prone to compaction due to frequent tillage and trampling [43]. Straw provides soil microorganisms with abundant energy (carbon source) and nutrients, thereby greatly stimulating soil biological activity. Long-term field trials have shown that returning straw to the soil can significantly increase soil microbial biomass, diversity, and community activity [42,44]. Enhanced microbial activity accelerates the decomposition of soil organic matter and the mineralization cycle of nutrients, and increases the activity of various enzymes such as urease, phosphatase, and sucrase in the soil [45–47]. This increase in microbial activity may be the core mechanism by which straw return improves soil health and enhances soil fertility. Straw return to the field is also considered to promote nutrient recycling and efficient absorption on multiple levels. On the one hand, straw itself is a carrier of nutrients. The nitrogen, phosphorus, potassium, and other elements released after its decomposition are an important supplement to crop nutrition, reducing dependence on chemical fertilizers [48]. On the other hand, the organic matter produced by straw decomposition can adsorb NH_4^+-nitrogen, reducing its volatilization losses. By providing a carbon source for denitrification, nitrogen may be released in the form of N_2, thereby reducing the production of the potent greenhouse gas N_2O, and improved soil structure also reduces nitrogen leaching losses [49,50]. In this study, we found that tillage and straw incorporation may exhibit synergistic effects. Deep tillage can uniformly incorporate straw into the deeper soil layers, addressing the issue of straw affecting seeding operations at the surface while placing organic matter in a more stable and moist soil environment, which facilitates its decomposition and humus formation. Additionally, the deeper soil layers are improved by the introduction of external organic carbon. In terms of crop yield, this approach outperforms individual measures. This combined approach is considered an effective strategy for achieving soil structure improvement and soil fertility enhancement.

A large number of changes occurred in the structure of the soil microbial community at the phylum level in this study through the application of 20% nitrogen reduction, *Bacillus megaterium*, and a combination of deep plowing and straw return. The relative abundance of *Acidobacteria* and *Bacteroidetes* increased, while that of *Actinobacteria* and *Firmicutes* decreased in bacteria; In fungi, the relative abundances of *Ascomycota* and *Mortierellomycota* increased, while those of *Chytridiomycota* and *Basidiomycota* decreased, which were consistent with some previously reported mechanisms. The *Acidobacteria* phylum has been associated with poor, acidic soil environments, and it is considered typical oligotrophic microorganisms that have a competitive advantage under low-nutrient conditions [51]. Soil pH is a key predictor of bacterial community structure, with *Acidobacteria* being more abundant in low pH soils and *Actinobacteria* being more abundant in high pH soils [52]. Nitrogen reduction treatment typically increases soil pH, which is consistent with the increase in *Acidobacteria* and decrease in *Actinobacteria* that we detected. *Bacteroidetes* are typical eutrophic bacteria, and their abundance is positively correlated with carbon mineralization rates. Straw incorporation may promote the proliferation of *Bacteroidetes* by providing easily degradable carbon sources [53]. Other studies have suggested that nitrogen application significantly increases the abundance of *Firmicutes*, while nitrogen reduction decreases its abundance, which is consistent with the pattern we observed. We speculate that *Firmicutes* (such as *Bacillus* spp.) proliferate under nitrogen-sufficient conditions, while nitrogen reduction inhibits their growth; simultaneously, the application of *Bacillus* inoculants may reduce the abundance of indigenous *Firmicutes* through competitive exclusion. Yang et al. found that straw return significantly increased the abundance of *Ascomycota* and *Mortierellomycota*. Dong et al. also confirmed that high nitrogen levels inhibit the growth of *Ascomycota*, while reduced nitrogen levels alleviate this inhibitory effect. *Ascomycota* is the dominant group of saprophytic fungi [54], it can efficiently decompose lignin and cellulose in straw, accelerate the mineralization of organic matter, and improve soil fertility. Many *Chytridiomycota* are aquatic or parasitic fungi. Deep plowing improves soil aeration and reduces their adaptability [55]. *Basidiomycota*, including some pathogens, depend on high-nitrogen environments, and nitrogen reduction inhibits their proliferation. At the same time, *Bacillus* bacteria secrete antimicrobial substances, which may further inhibit their abundance [56,57].

In addition to the results present in this study, we have noticed that cadmium accumulation rates of 0.0289 $mg \cdot kg^{-1} \cdot year^{-1}$ in Shandong greenhouses [58] imply similar risks in Hebei, potentially interacting with salinity to constrain microbial recovery. Additionally, the experiments' confinement to cucumber monoculture limits extrapolation to diversified rotations. Pu et al. demonstrated that legume intercropping enhances the benefits of nitrogen reduction through symbiotic nitrogen fixation [59]. Such potential synergy is to be explored in the future.

5. Conclusions

In conclusion, our research validates a synergistic soil management strategy capable of reversing the trajectory of degradation in intensive greenhouse soils. The key findings robustly demonstrate a progressive enhancement of benefits: (1) A 20% nitrogen reduction effectively mitigating topsoil salinization and reshaping the soil microbial community without compromising cucumber yield. This challenges the conventional reliance on high fertilizer inputs and establishes a foundation for further improvements. (2) The synergy between this nitrogen reduction and *Bacillus megaterium* inoculation amplifies greater potential, significantly reducing the global warming potential while simultaneously boosting yield. (3) The most comprehensive benefits are realized by integrating reduced nitrogen, deep tillage, *B. megaterium*, and soybean straw. This holistic approach synergistically enhances soil physical structure, optimizes nutrient cycling and use efficiency, and culminates in the highest crop performance among all treatments.

This integrated approach provides a viable and scalable solution to reverse soil degradation caused by decades of over-fertilization. By addressing the root causes of the problem, physical, chemical, and biological, it offers a practical pathway for the sustainable intensification of facility agriculture in northern China and other regions facing similar challenges, ensuring long-term productivity and ecological resilience.

Author Contributions: Z.P. and X.F. designed the experiments. Y.W. provided the experimental materials. Y.Y. and R.G. were responsible for data collection and data curation. T.S. performed the data analysis. Y.Y. drafted the original manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Key R&D Program of Hebei Province (no. 19226912D) and the Agricultural Sci-Tech Achievement Transformation Fund of Hebei Province (2022-2025), both administered by the Hebei Provincial Department of Science and Technology.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding authors.

Conflicts of Interest: Authors declare that there is no conflict of interest.

Appendix A

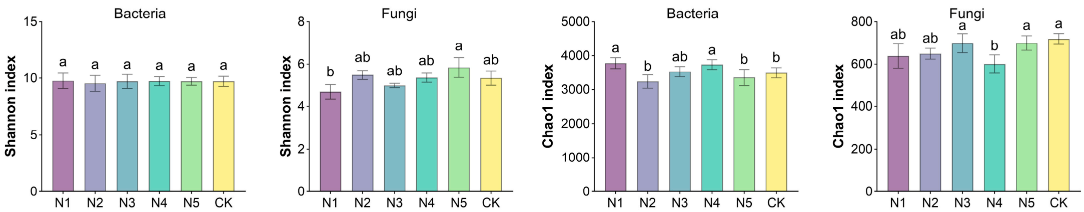

Figure A1. The effect of reduced nitrogen fertilizer application on the Shannon and Chaos1 indices of soil bacteria and fungi. Statistical significance was assessed by one-way ANOVA followed by Duncan's test. Different lowercase letters denote significant differences ($p < 0.05$) between groups, while shared letters indicate no significant difference.

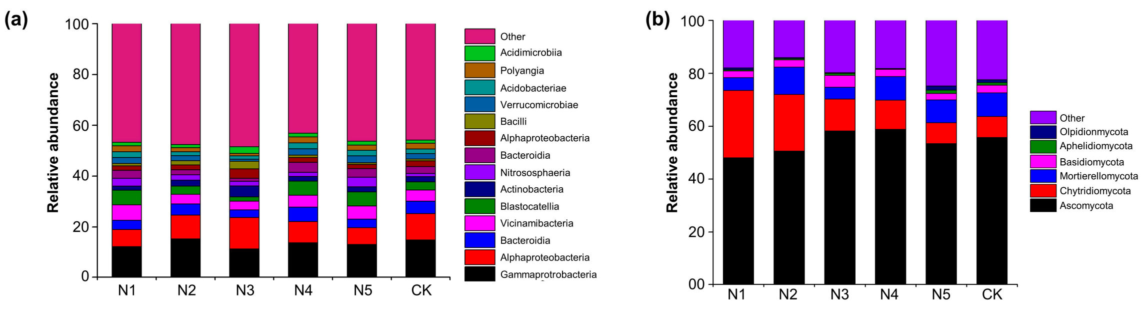

Figure A2. Impact of nitrogen fertilizer reduction on soil microbial community at class level. Effect of reduced nitrogen fertilizer application on the relative abundance of bacteria (**a**) and fungi (**b**) evaluated at class level.

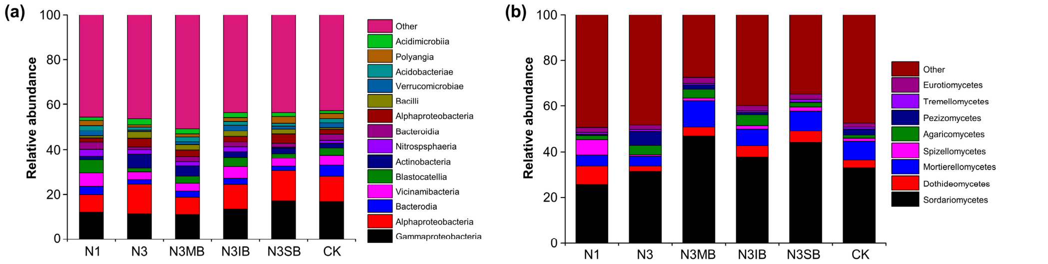

Figure A3. Impact of *Bacillus* inoculants on soil microbial community at class level. Effect of *Bacillus* inoculants on the relative abundance of bacteria (**a**) and fungi (**b**) evaluated at class level.

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