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Article

Evaluation of Green Soybean (*Aodaizu*) Parameters under Mechanized Deep Placement Fertilizer Application: Insights from Remote and Ground Surveys

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Abstract: Sustainable agriculture is at the forefront of modern farming practices, with a growing emphasis on optimizing crop production while minimizing environmental impact. The choice of fertilizer application technology plays a critical role in achieving these objectives. Soybean (Glycine max (L.) Merr.), a valuable crop globally, serves both as a source of human nutrition and livestock feed. To address the challenges of enhancing soybean production while minimizing ecological harm, this study evaluates and compares the performance of different fertilizer application technologies. In this study we combined remote and ground surveys to allow a comprehensive understanding of the impact of these technologies on soybean cultivation. The study focuses on deep placement of slow-release nitrogen fertilizers with coated urea at a 20 cm depth, conventional nitrogen fertilizer application, and manure organic fertilizer application. Remote surveys are conducted using advanced smart farming tools such as Unmanned Aerial Vehicle (UAV), ground surveys such as soil plant analysis development SPAD measurements, and soybean parameters to assess the impact of fertilizer application. This study revealed that deep placement fertilizer demonstrated better performance compared to other fertilizer application technologies for soybean cultivation. The findings from this study contribute to the advancement of sustainable agricultural practices and empower farmers with knowledge to make informed decisions for optimizing green soybean production.

Keywords: agriculture; deep placement fertilizer; NDVI; SPAD; soybean

1. Introduction

Soybean is one of the most important legumes globally and the fourth crop next to rice, wheat, and maize in terms of global crop production. Soybean as one of the most important leguminous grain crops is used by human beings and livestock as food or feed, respectively, worldwide [1–4]. Soybean is a crop that has been cultivated for a long time, and there are a wide variety of cultivars, and the colors of seeds such as yellow, green, blue, brown, red, and black, and color tones are also rich in variety [5]. Yellow soybeans are the most commercially grown in large quantities. Typically, yellow soybeans turn green as they mature into seeds but turn yellow when fully ripened and dried. However, green soybeans retain their green color even when fully ripened. There are varieties of blue soybeans that have green outer skin and cotyledons [5]. Green soybeans are low in fat and have a sweet taste. It also contains many functional ingredients such as "soy isoflavones", which function similarly to female hormones, and "soy saponins", which can be expected to have antioxidant effects.

This legume crop can assimilate both nitrogen (N) biologically fixed in the root nodules and inorganic nitrogen absorbed by roots from soil and fertilizer [6]. The biologically fixed nitrogen (BFN) that is absorbed from the air stores the nitrogen in nodules on their roots, with the help of special bacteria (Rhizobia). As the root nodules grow, it starts to produce nitrogen. The root provides the rhizobium bacteria with food and shelter and in return the bacteria help the plant to store nitrogen [7,8]. The nitrogen that the legume crop absorbs from the air is used for its growth and is stored in the root nodules. When the crop is harvested the roots are left in the ground, where they decompose, releasing the nitrogen into the soil, this nitrogen can then be used by the next crop that is planted in the same field [9,10]. It also absorbs inorganic nitrogen (N) taken up by roots from soil and fertilizer [11].

Introduction of new methods of fertilizer application technology, such as deep placement fertilizer technology (DPFT) of slow-release fertilizers of lime nitrogen (LN), coated urea, calcium cyanamide ($Ca(CN)_2$), potassium (K_2O) and phosphorus (P_2O_5) at 20 cm depths has a positive effect on crop growth, seed quality, yield of soybean plants and environmental aspects, this new method was developed by [12]. The positive effects of deep placement fertilizer technology of slow-release fertilizer are reached by the usage of precision fertilizer fixation during plant development stages, especially in the reproductive stages from, reproductive stage 1 (R1) to reproductive stage 6 (R6) [11–15]. The concept of DPFT of slow-release nitrogenous fertilizers is likely to be adopted to reduce environmental and water bodies pollution as well as to enhance nitrogen use efficiency (NUE) [16].

Nitrogen fertilizers containing nitrate are more prone to leaching whereas nitrogenous fertilizers containing amide and ammonium are more prone to volatilization. Hence, slow-release nitrogen fertilizers reduce the nitrogen losses and increase the nitrogen recovery thereby increasing the nitrogen use efficiency. Slow-release nitrogen fertilizers can reduce the nitrogen losses due to the delayed nitrogen release pattern which synchronizes the crop demand and soil nitrogen supply [17].

Lime nitrogen (LN) has been produced by artificial nitrogen fixation where calcium cyanamide ($Ca(CN)_2$) is converted to urea in soil, then the urea is hydrolyzed to ammonium and carbon dioxide [15]. In the presence of moisture and air, dicyandiamide is formed from calcium cyanamide (CaCN_2), and this is a potent nitrification inhibitor, which inhibits the oxidation of ammonium to nitrate. The ammonium produced by calcium cyanamide (CaCN_2) decomposition persists for a long period and the nitrate concentration remains low in soil [15].

Furthermore, to optimize nitrogen (N) fertilizer rate based on the assessment of nitrogen (N) needs by using site-specific nutrient management methods, handheld optical crop sensors are user-friendly devices that enable diagnosis of crop health and nutrient needs [18]. Optical crop sensors evaluate crop conditions by shining specific wavelengths of light such as red, and infrared at crop leaves and measuring the type and intensity of the light wavelengths reflected by the sensors [18]. Healthy plants absorb more red light and reflect larger amounts of near-infrared light than unhealthy plants. These reflectance characteristics are used to develop vegetative indexes such as the normalized difference vegetation index (NDVI) and SPAD to assess plant health [18,19]. Using a SPAD meter, the sensor establishes a chlorophyll amount reference area in the field [14].

The use of innovative technologies such as hand-held crop sensors and UAV sensors has gained significant attention in precision agriculture. While existing research has explored the potential benefits and efficiencies of these technologies in a variety of crop production contexts, there remains a relative lack of empirical investigation into their impact specifically on green soybean cultivation. This research aims to bridge this knowledge gap by studying the impact of DPFT with slow-release fertilizers on green soybean productivity. By doing so, this work contributes to our understanding of how these technologies can be effectively utilized to enhance crop yield, improve nutrient use efficiency, and reduce environmental impacts in soybean production, thereby supporting sustainable and productive agricultural practices. Therefore, this study aims to assess soybean yield productivity under different fertilizer technologies and evaluate soybean crop performance through assessments of chlorophyll content by SPAD, NDVI.

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2. Materials and Methods

2.1. Climate Condition of the Experimental Site

The climate condition in Niigata–Muramatsu is typical for mountainous regions, with very harsh winters and hot, humid summers, especially from June to September. The average temperature during the summer season is 24° C and the average precipitation is 220 mm. The climate characteristics of the experiment site are shown in Figure 1. The weather data used in this study was collected through the AMeDAS (Automated Meteorological Data Acquisition System) station in Japan. In August 2023, there was no precipitation, which adversely affected the study's outcomes, particularly in soybean cultivation.

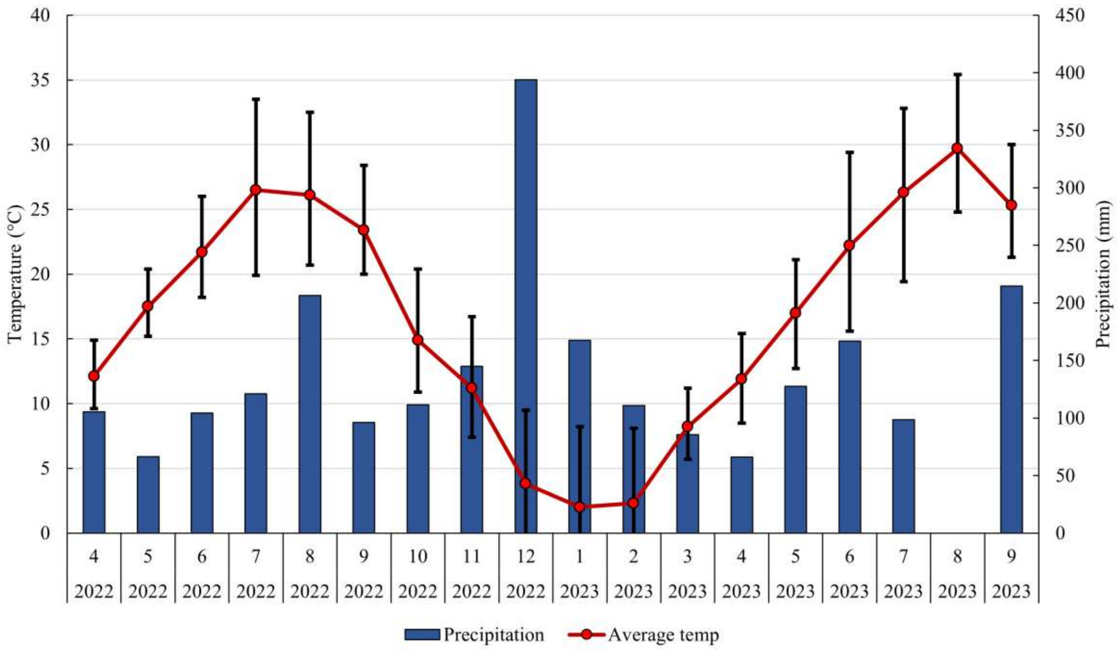

Figure 1. Average monthly weather data from 2022 to 2023 for Niitsu city, Niigata Prefecture, Source: AMeDAS station.

2.2. Experimental Site and Treatments

The field experiment was conducted over two years from 2022 to 2023 at Niigata University Experimental Farm - Muramatsu station in Niigata, Japan (Latitude: 37.692820, Longitude: 139.193045) (Figure 2). The seedings were carried out between the 5th and 7th of June, and the harvesting took place around the 20th of November for both years.

Figure 2. Muramatsu field experimental site location on the world map based on Bing basemap. Muramatsu station map taken by drone by the Laboratory for Bioproduction and Machinery at Niigata University, 2023.

Two fields were used for this experiment in 2022 and 2023. In this study, the fields selected for experimentation were real farmland production sites. In the 2022 experiment, conducted across two distinct fields, a total of 5 observation plots were employed to investigate the impact of different fertilizer application technologies on green soybean cultivation. Within this setup, two of the plots were allocated for conventional fertilizer application, two for the use of compost as a fertilizer method, and one plot was dedicated to DPF technology (Figure 3).

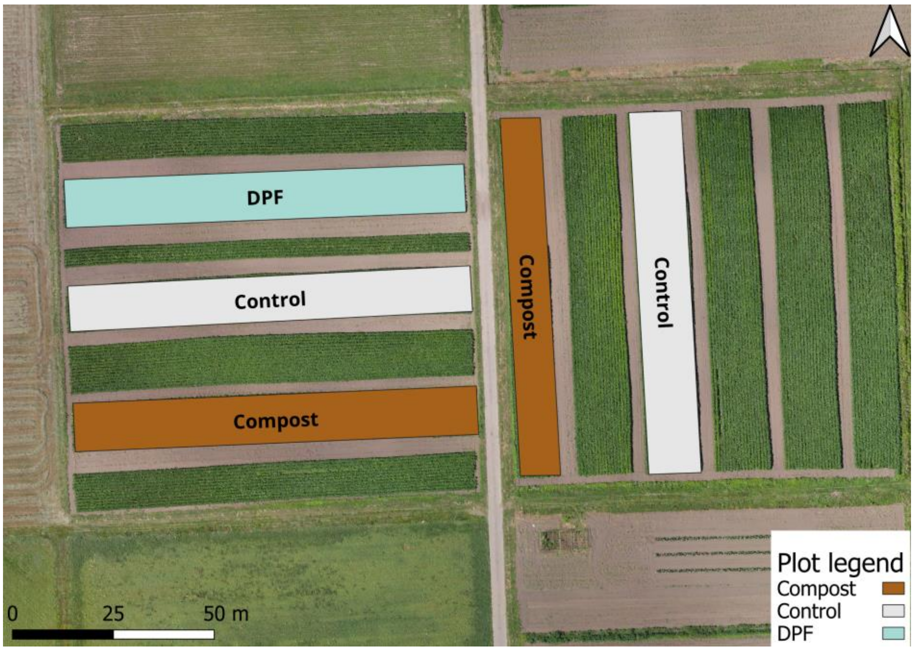

Figure 3. Experimental design of plots for the 2022 season. Fields image taken by drone by the Laboratory for Bioproduction and Machinery at Niigata University, 2022.

In the 2023 experiment, the research design expanded significantly to include a total of 10 observation plots. Within this expanded setup, there were three plots dedicated to conventional fertilizer application, three plots for compost application, and three plots for DPF. Additionally, one

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plot combined the DPF method with compost application. The expanded number of plots in the 2023 experiment was designed to offer a more comprehensive assessment of the various fertilizer application technologies, allowing for an enhanced evaluation of their effects on soybean cultivation and yield during the 2023 growing season (Figure 4).

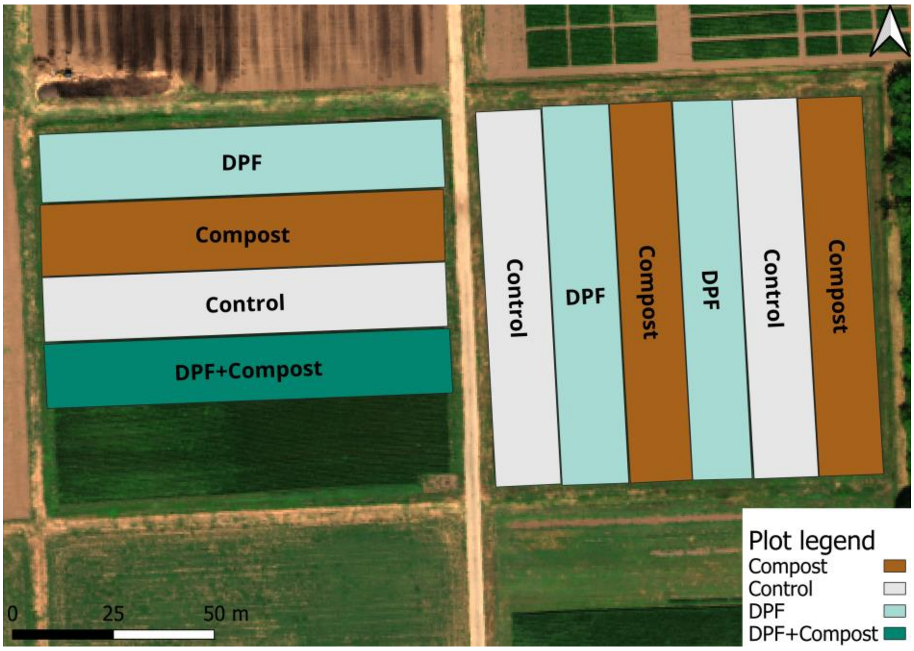

Figure 4. Experimental design of plots for the 2023 season. Source: fields image taken by drone by the Laboratory for Bioproduction and Machinery at Niigata University, 2023.

Manure fertilizer Technology (MFT) from cows was applied in the compost treatments two weeks before planting. Bulk organic manures, such as those from cows, have an important place in the nutrient management of soybeans. Compost is an essential source of organic matter, plant nutrients, and microbes that stimulate plant growth [20,21]. Compost has proven to be a useful ingredient for making commercial organic fertilizers and amendments [22,23], and it's also a good substitute for peat when it comes to carrying rhizobia inoculants [24]. The chemical composition of the manure is given in Table 1. Conventional fertilizer application of Nitrogen, Phosphorus, Potassium, and Boron, has the following chemical composition (NPKB) - (8%, 20%, 30%, 0.7%). Nitrogen is directly proportional to the chlorophyll content of soybean plants, and it participates in almost all the metabolic processes of the crops including photosynthesis activity [19]. Phosphorus plays a crucial role in the growth process of plants. It is responsible for the structural development of plants, and seeds hold the highest concentration of phosphorus in a mature soybean plant. Phosphorus is also essential for energy transformation, root growth, and controlling physiological reactions. It can improve a plant's resistance to various abiotic stressors, such as heat, salinity, drought, waterlogging, and heavy metal toxicity [25,26]. Soybean requires potassium for a variety of processes, including protein synthesis, starch production, water nutrient translocation, and cell turgidity. Potassium supports nutrient absorption and helps to fight against crop diseases, pests, and water stress. Boron is a crucial component of many physiological processes, it is an essential nutrient for terrace construction. In addition to its significant role in cell wall biosynthesis, boron is also involved in the synthesis of carbohydrates, nodulation formation, nitrogen fixation, membrane function, tissue differentiation, root elongation, pollen germination, and soybean growth [27].

Table 1. Results of laboratory analyses of manure quality used to fertilize the fields before soybean sowing.

Cow manure quality parameters	Values	Dry Matter Values
pH, units	8.82	
EC, ms/cm	7.04	
Moisture, %	67.98	
Total Nitrogen, %	0.485	1.516
Soluble phosphorus (P_2O_5), %	0.356	1.111
Soluble potassium (K_2O), %	0.848	2.649
Component, %	7.48	23.36
Calcium (CaO), %	0.921	2.878
Total fluorine, %	13.53	42.25
N/Ratio	27.87	
Magnesium (MgO), %	0.238	0.743
Manganese (Mn), ppm	116.824	364.902
Zinc (Zn), ppm	38.209	119.345
Copper (Cu), ppm	6.381	19.931
Iron (Fe), %	0.095	0.297
Nickel (Ni), ppm	4.113	12.847
Cobalt (Co), ppm	3.045	9.513
Nitrate nitrogen, ppm	11.968	37.381
Ammonia nitrogen, ppm	20.613	64.385
Inorganic nitrogen, ppm	32.584	101.760

In DPFT of slow-release nitrogen and calcium cyanamide, around 30 kg was applied in one plot at a depth of 20 cm. The seed placement depths were achieved by deep placement fertilizer applicator (Figure S1), the management of fertilizer application should take into account the best possible ratio of fertilizer periods and rates, as well as evaluate the equipment and application techniques to maximize efficiency (precise methods), applying fertilizer effectively is essential for crop productivity, financial gain, and environmental benefits [12,28,29]. The fertilizer's chemical formula, quantity, size, timing, and placement all have an impact on how effectively it is used, which in turn affects crop output, crop production, and soil health to reduce adverse environmental consequences and increase farm profits. Thus, a deep placement fertilizer technique (DPFT) is among the best currently available management fertilizer technologies that accomplish these numerous advantages [12,28,29]. Research has shown that applying coated urea, lime nitrogen, phosphorus, and potassium as a deep controlled-release (slow-release) fertilizer at a depth of 20 cm improves plant growth, seed quality, and yield in soybean plants. The encouragement of precise fertilizer fixation during all plant development stages, especially during the reproductive phases (R1–R6), was responsible for achieving these beneficial outcomes [28,30]. The chemical properties of slow–release Calcium Cyanamide contain 50% alkali and 21% nitrogen. The physical properties include a pouring density of 1000 Kg/m^3 and a grain size of 0 to 3.5 mm.

2.3. SPAD Measurements

To precisely estimate leaf chlorophyll concentrations, sensor technologies have come into play in the form of a SPAD chlorophyll meter [31]. The SPAD chlorophyll meter has been used since the 1990s by researchers [31,32] and farmers to help estimate the nitrogen (N) content of plants. It instantly measures chlorophyll content or plants' "greenness" to reduce the risk of low yield or the use of excess fertilizers [31,33]. The SPAD quantifies subtle changes or trends in plant health long before these are visible to the human eye. By clamping the meter over the leafy tissue of green plants, a noninvasive and nondestructive measurement can be taken, which provides an indexed chlorophyll

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content reading in less than two seconds. Thus, SPAD is used to assess nitrogen (N) needs, and research shows a strong correlation between SPAD measurements and leaf nitrogen (N) content [33].

The chlorophyll content of soybean leaves was measured in this study utilizing a Soil Plant Analyzer Device (Chlorophyll Meter SPAD-502Plus (KONICA MINOLTA INC. Tokyo, Japan), which is a lightweight handheld chlorophyll meter that does not harm plants (Figure 5). The SPAD values were measured five times in 2022, on 14 July, 24 July, 24 August, 31 August, and 6 October. In 2023, the SPAD values were recorded on 24 July, 16 August, 30 August, 24 September, and 2 October. Each time, fifteen plants were randomly selected, and measurements were taken for each treatment plot. SPAD values were determined at the center part of three leaves at the second node from the top and then were averaged per trifoliate. We selected SPAD values for three particular days each year which are represented in Figures 8 and 9.

Figure 5. Soil Plant Analyzer Device (Chlorophyll Meter SPAD-502Plus, KONICA MINOLTA INC. Tokyo, Japan).

2.4. UAV Measurements

UAV technology and index applications are currently the most essential instruments in agriculture. The usage of the normalized difference vegetation index (NDVI) in agriculture is quickly growing, and the necessity to incorporate these technologies into agriculture is increasingly critical [19,34].

The Normalized Difference Vegetation Index (NDVI) which was observed using drone-based imagery was estimated based on the absorption and reflection of near-infrared and visible red light. These remotely sensed NDVI photos were captured using a DJI Matrice 300 RTK drone with a Micasense Rededge camera on board at a height of 40 meters. A software called DJIFlightPlanner was used to prepare the flight, and through the cloud service Mission Hub, it was uploaded to a smartphone. To align photos by matching features detected in overlapped areas of the images, we used Agisoft Metashape. The experimental field's orthophoto mosaic was then created, and the orthophoto map was obtained. This image was exported as a TIFF (Tagged image file format) file. This image consists of GPS metadata and the camera's five band reflectance readings (Red, Green, Blue, Infrared, and Rededge). The orthorectified photos were analyzed in QGIS (open-source GIS software) for vegetation index calculation. Drone surveys to get the NDVI values were carried out every week during the growing season from June to September.

Figure 6. DJI Matrice 300 RTK drone provided by the Laboratory for Bioproduction and Machinery at Niigata University.

3. Results

3.1. Soybean Yield

The study conducted in 2022 compared the effectiveness of three different fertilizer methods on soybean yield and yield components: deep placement fertilizer technology, compost application, and conventional fertilizer application. The results were encouraging, with both deep placement and compost treatments producing significantly higher yields 2.7 and 2.6 t/ha respectively compared to the conventional method 2.4 t/ha. This suggests that these innovative approaches have the potential to significantly improve soybean production. However, the study also highlighted the crucial role of weather conditions. In 2023, a lack of precipitation during the critical podding and seed-filling stages (July and August) significantly impacted yields across all treatments (Figure 1, August 2023). While deep placement combined with compost remained the most effective method, yielding 1.31 tons/ha, even this approach saw a decline compared to the previous year. Other yields recorded in 2023 were as follows: deep placement alone yielded 1.11 t/ha, compost alone yielded 1.1 t/ha, and the conventional method yielded 0.98 t/ha (Figure 7).

This underscores the vulnerability of soybean production to erratic weather patterns and emphasizes the need for further research into drought-resistant varieties and irrigation techniques. Interestingly, the study observed no significant differences in the 100-seed weight between treatments in either year. This suggests that while weather conditions may affect overall yield, the weight of individual seeds remains relatively consistent across different fertilization methods. Additionally, the study noted a higher 100-seed weight in 2023 compared to 2022. This anomaly is attributed to the incomplete drying of pods in 2023, highlighting the importance of accounting for moisture content when evaluating seed weight. Furthermore, the study provides promising evidence that deep placement and compost application can enhance soybean yields. However, the significant impact of weather conditions underscores the need for further research on mitigating the effects of drought and developing more resilient cropping systems. By combining innovative fertilization practices with drought-resistant varieties and sustainable water management strategies, farmers can improve soybean production and ensure long-term food security.

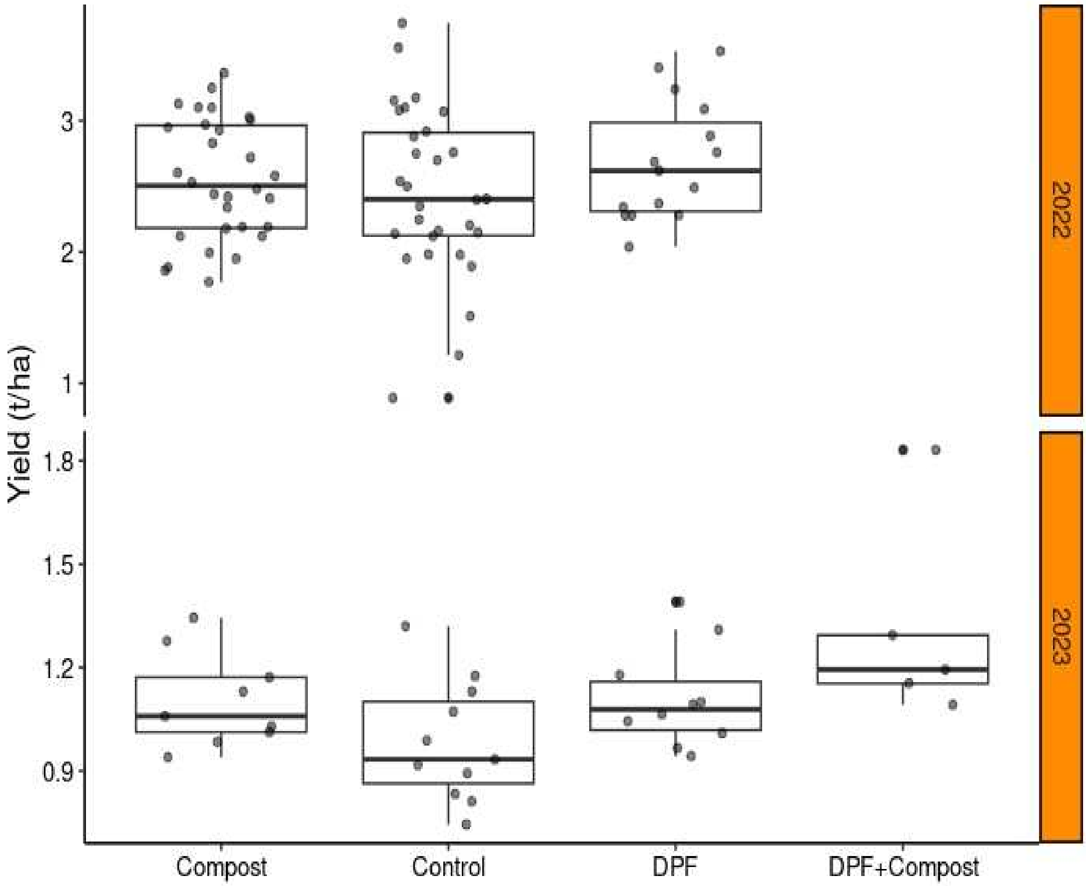

Figure 7. Soybean yield for 2022 and 2023 for Muramatsu ST. Source: data collected by the Laboratory for Bioproduction and Machinery, Niigata University.

3.2. Soil Plant Analysis Development (SPAD Values)

SPAD values, which reflect chlorophyll content, varied between 32.32 and 46.62 for both seasons. The box plot graphics below illustrate the effect of different fertilizer applications on SPAD values. Measurements were taken on different days for four treatments: deep placement fertilizer combined with compost, deep placement fertilizer alone, compost alone, and conventional fertilizer. SPAD values also exhibited variations across four different growth stages, as shown in Figures 8 and 9. During the initial growth to the development stage, conventional and compost fertilizer treatments showed an increase in SPAD values, followed by a decrease as the plants reached the reproductive stage. In contrast, SPAD values for deep placement fertilizer technology showed a steady increase from 24 July to 31 August 2022. Similar results were observed in the 2023 cropping season, where SPAD values increased continuously from 16 August to 24 September. These observations suggest that deep placement of slow-release lime nitrogen fertilizer delays the availability of plant nutrients. After hydrolysis begins, the fertilizer gradually releases nutrients into the soil, making them available for crop growth during the reproductive stages (R1 to R6), when pod formation and seed filling occur.

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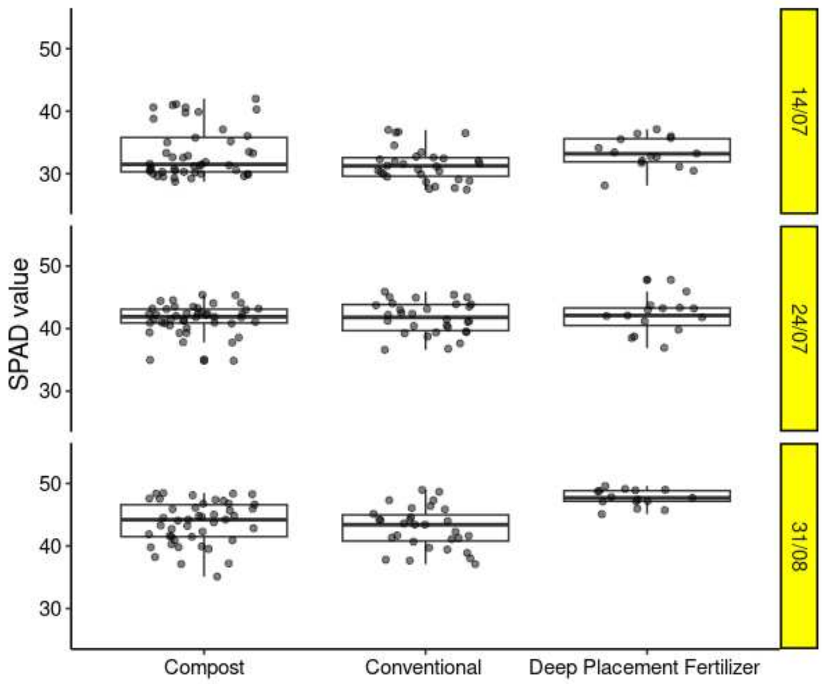

Figure 8. SPAD measurements for 2022 of soybean plants at Muramatsu ST. Source: data collected by the Laboratory for Bioproduction and Machinery, Niigata University.

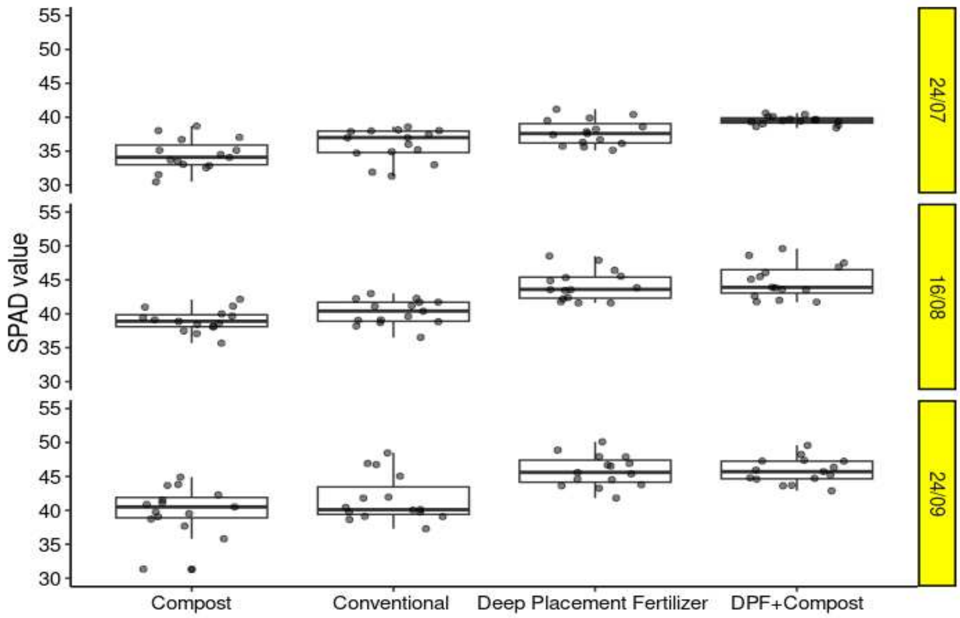

Figure 9. SPAD measurements for 2023 of soybean plants at Muramatsu ST. Source: data collected by the Laboratory for Bioproduction and Machinery, Niigata University.

3.3. Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) ranges from -1 to 1, with 1 indicating highly dense vegetation and -1 indicating very sparse vegetation. Values closer to 0 on vegetation indices, such as NDVI, generally imply lower canopy density, whereas values closer to 1 suggest higher canopy density for crops [19,35]. Throughout the soybean growing season, NDVI values increased as the plants developed. The NDVI values for the 2022 season showed an upward trend during the initial stage, ranging from 0.74 for compost and 0.75 for deep placement fertilizer (DPF). The control plot exhibited the lowest value of 0.68. In the R2 stage (59 days after planting), NDVI values for DPF and compost plots were similar at the sampling points, recording a value of 0.91,

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while the control plot showed the lowest value of 0.89. Small variations in NDVI values were observed between treatments in the final stage of the growing season. For the 2023 cropping season, the range in NDVI values was greater at vegetative stage 1 than at the other growth stages, likely due to the relatively dry conditions. There were similarities in NDVI values for DPF and compost treatments, followed by deep placement combined with compost, while the lowest values were recorded for the conventional fertilization method (Figures 10 and 11).

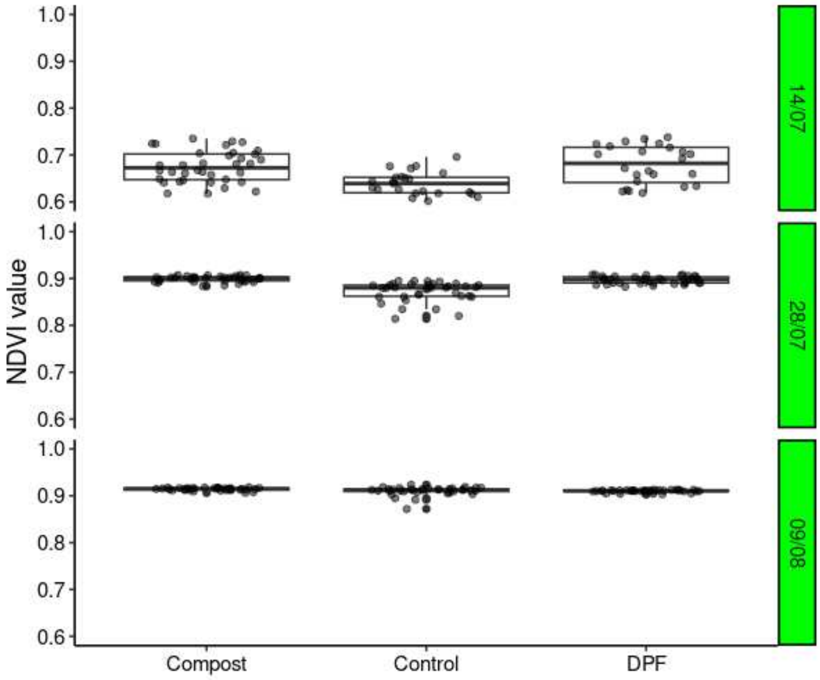

Figure 10. NDVI for 2022. Source: data collected by the Laboratory for Bioproduction and Machinery, Niigata University.

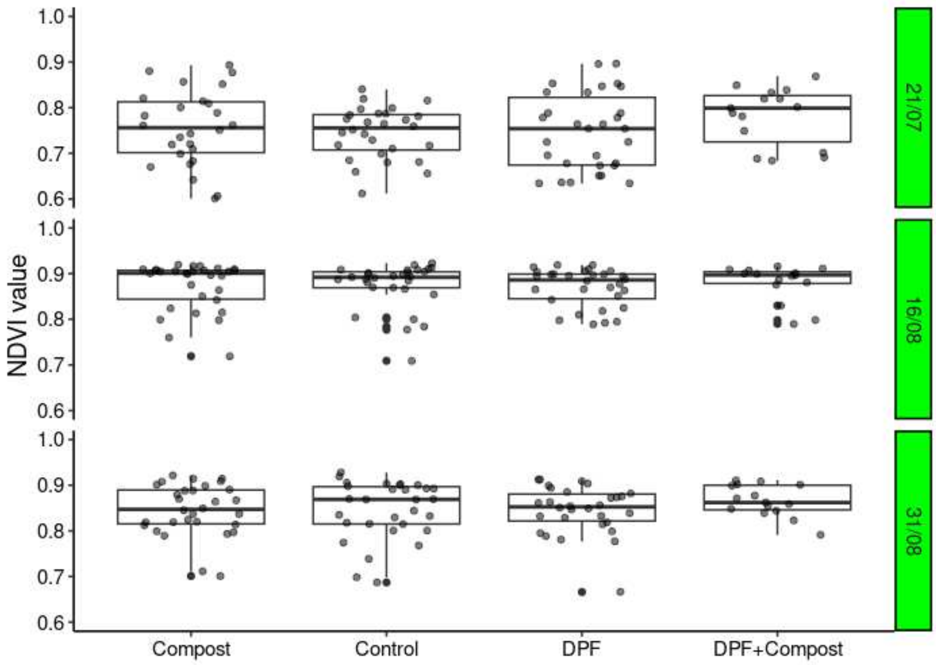

Figure 11. NDVI for 2023. Source: data collected by the Laboratory for Bioproduction and Machinery, Niigata University.

3.4. Relationship Between Below and Aboveground Parameters

Pearson correlation coefficient was computed to determine the relationship between growth parameters of soybean and vegetation activity indicators SPAD and NDVI. The results for the 2022 and 2023 cropping seasons revealed a significant positive correlation between all the soybean parameters tested across different fertilization methods. A closer examination of the effects of SPAD and NDVI on yield, hundred-grain weight, and height indicated that SPAD exhibited a strong positive correlation with yield, showing correlation coefficients of 0.93, and 0.9, for deep placement and conventional fertilization method respectively, and a moderate correlation of 0.67 was observed for compost.

Similarly, SPAD showed a very high correlation with hundred-grain weight, with a correlation coefficient of 0.95 for the conventional fertilization method, a high correlation coefficient of 0.85 for deep placement, and a moderate correlation coefficient of 0.6 for compost. The correlations between SPAD and height were moderate for compost and conventional fertilizer treatments, with correlation coefficients of 0.54 and 0.67 respectively, while deep placement showed a high correlation coefficient of 0.8. NDVI also demonstrated a strong positive correlation with yield. A moderate correlation coefficient of 0.62 for the conventional fertilization method was observed, and very high correlation coefficients of 0.92 and 0.94 for deep placement, and compost fertilization methods, respectively. Moreover, NDVI exhibited a strong positive correlation with hundred-grain weight, with very high correlation coefficients of 0.9 and 0.93 for deep placement and conventional fertilization methods, respectively, and a high correlation coefficient of 0.89 for compost.

Furthermore, the correlations between NDVI and height were significant across all fertilizer treatments, with high correlation coefficients of 0.7 and 0.77 for compost and conventional fertilization methods respectively, and a very high correlation coefficient of 0.9 for deep placement. In the 2023 cropping season, the correlation between NDVI and height was high with a regression coefficient of 0.88 for compost and deep placement, on the other hand, the conventional fertilization method and deep placement combined with compost showed very strong correlation coefficients of 0.9, and 0.91 respectively. The correlation between NDVI and hundred–grain weight showed high correlation coefficients of 0.76 and 0.82 for compost and deep placement combined with compost respectively, while the conventional fertilization method and deep placement recorded moderate regression coefficients of 0.54 and 0.67 respectively.

The correlations between SPAD and height were moderate across all fertilizer treatments, with correlation coefficients of 0.75 and 0.77 for compost and deep placement respectively while, 0.79 was the correlation coefficient for conventional fertilization method and deep placement combined with compost. Similarly, SPAD showed a high correlation with hundred–grain weight with correlation coefficients of 0.71, 0.72, and 0.74 for conventional fertilization method, deep placement combined with compost and compost respectively, except for deep placement which exhibited a moderate correlation coefficient of 0.67.

In conclusion for the 2022 cropping season, NDVI, height, and yield of soybeans exhibited the strongest correlations among the examined parameters. This observation could be attributed to the sensitivity of NDVI to biomass production and leaf area index (Figure 12). For the 2023 cropping season, the correlation between the vegetation activity indicators, namely SPAD and NDVI, and the hundred-grain yield were almost similar. However, the performance of Pearson correlation functions was affected by the lack of precipitation, especially during the flowering to podding and seed production stages. This is a crucial issue, as the agriculture sector is highly vulnerable to the impacts of climate change. (Figure 13).

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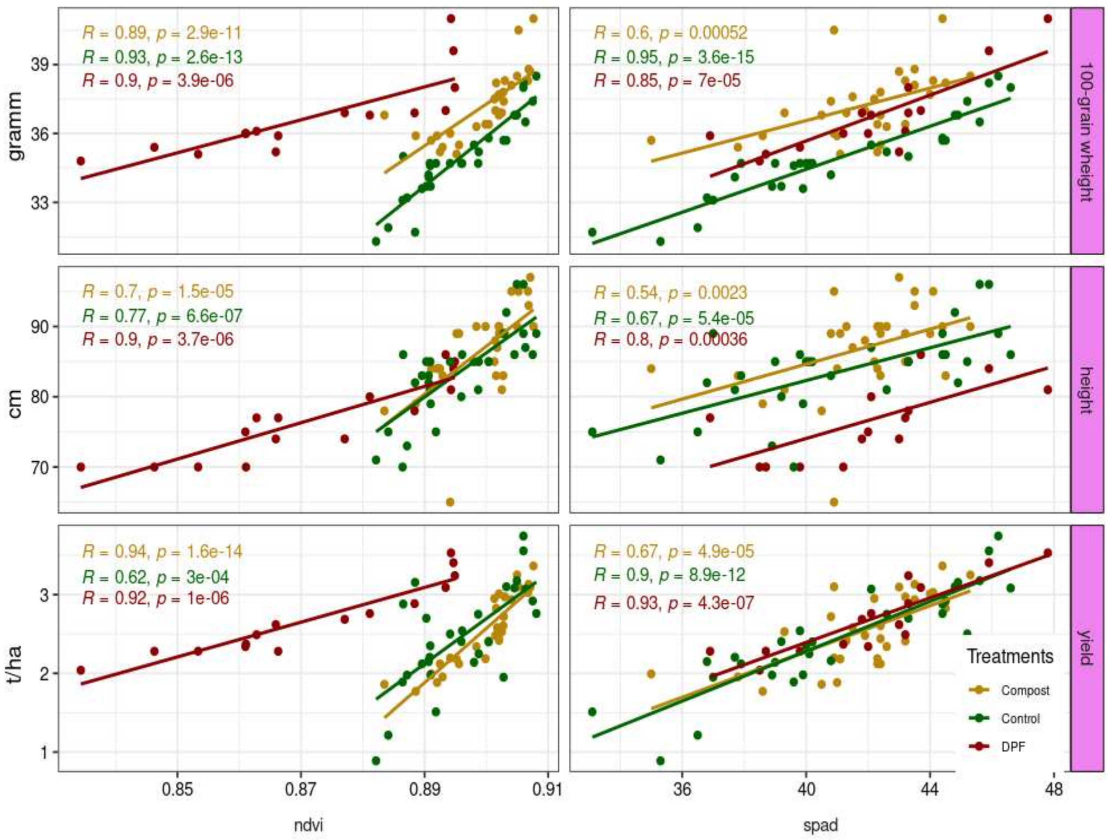

Figure 12. Relationship between SPAD, NDVI, Seed yield, and height under different fertilizer technologies for 2022.

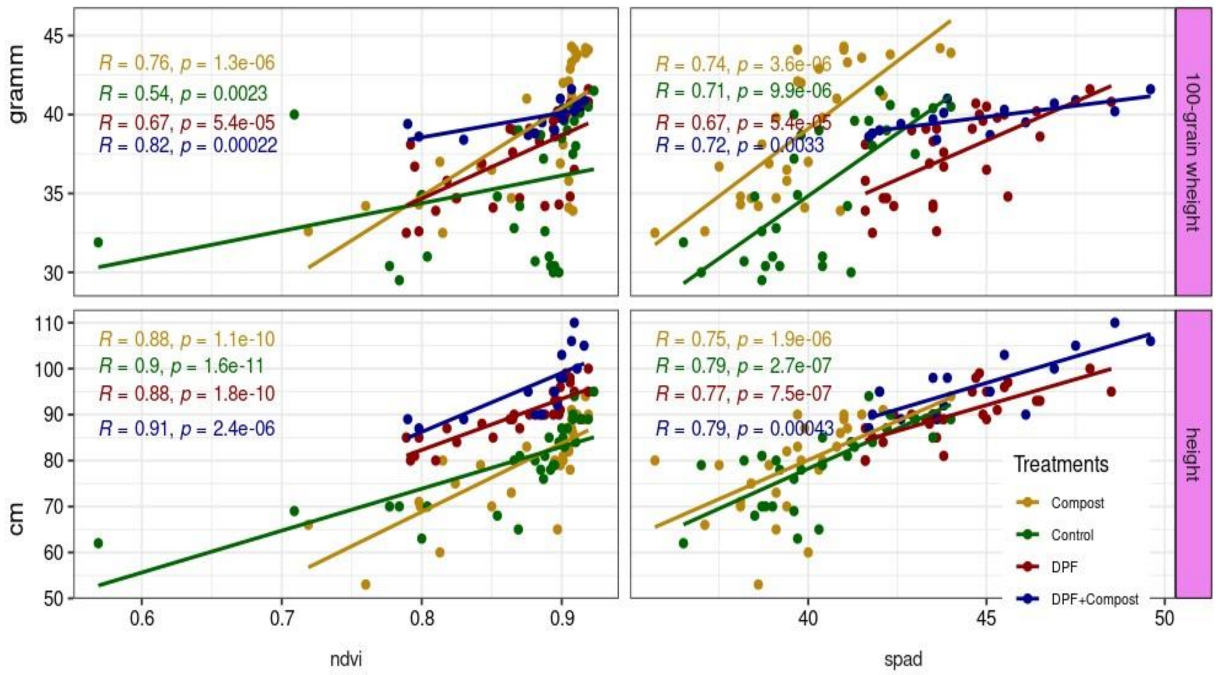

Figure 13. Relationship between SPAD, NDVI, Seed yield, and height under different fertilizer technologies for 2023.

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4. Discussion

The utilization of deep-placement fertilizer techniques has long been acknowledged for its positive impact on various aspects of soybean cultivation [36]. It has been demonstrated that using this technique can greatly improve soybean plant pod setting and seed yield. Furthermore, the processes of nodulation and nitrogen fixation—both essential to the growth and development of the plant—are enhanced by deep placement fertilizer procedures [37]. By increasing photosynthetic activity in both nodules and pods, this method ensures a continuous supply of nitrogen (N) from the lower part of the roots, further boosting soybean productivity [38].

The use of slow-release nitrogen, which is essential for effective nitrogen assimilation, especially during the reproductive stage of soybean growth, is one of the main benefits of this method. In addition to promoting healthy plant growth, slow-release nitrogen improves nodulation and nitrogen fixation. In addition, nodulation and nitrogen fixation are maintained through the prevention of nitrification, the process that turns ammonia into nitrates [39]. Furthermore, it has been discovered that applying calcium cyanamide has anti-macrobiotic characteristics and controls plant diseases, which enhances the overall health and productivity of soybean crops [14].

Research comparing various ways of fertilization has demonstrated positive results when it comes to deep placement techniques. [30] showed that soybean crops treated with deep placement fertilizers with controlled release had noticeably larger seed weights than those treated with traditional fertilization techniques. It's interesting to note that soybeans treated with deep placement fertilizer techniques and those treated with organic compost did not significantly differ in the weight of one hundred seeds. Further investigations revealed the efficacy of specific slow-release fertilizers such as lime nitrogen (LN) and coated urea (CU) in enhancing soybean yields. [40] demonstrated that these fertilizers increased soybean yields by an impressive range, from 10% to 120% higher than those achieved through conventional fertilization methods. [41] recorded higher grain yield and hundred-grain weight in soybeans treated with deep placement of coated urea (CU) and lime nitrogen (LN) in comparison to control plots and conventional top-dressing plots. Although no statistical differences were found among the treatments, the consistently positive outcomes emphasized the potential of these slow-release fertilizers in soybean cultivation. In addition, a separate study conducted over two consecutive years confirmed the superiority of deep placement techniques involving coated urea fertilizer compared to conventional fertilization and top-dressing methods. These experiments consistently showed higher yields in soybeans treated with deep placement of coated urea fertilizer, highlighting the sustained benefits of this approach [42].

Furthermore, studies on when to use slow-release fertilizer provided insightful information. When compared to compost and conventional fertilization methods, delaying the delivery of slow-release fertilizer—specifically, lime nitrogen (LN)—within the deep placement treatment produced better SPAD values, especially during the reproductive period. Improved SPAD values at different phases of soybean cultivation were also a result of increasing the nitrogen (N) delivery rate, highlighting the importance of effective nutrient management for optimum plant health and productivity [14].

[43] conducted an experiment to see how using cow manure as a fertilizer affects soybean plants. They discovered that the soybean plants grew higher and produced more pods, seeds, and overall seed weight when fertilized with 5000 kg/ha of cow manure. However, using this strategy resulted in a reduced weight for 100 seeds. Similar research revealed that applying a unique fertilizer technique known as deep placement significantly enhanced soybean seed production. Using machinery, fertilizers were inserted deeply into the soil using this technique. [44] discovered that, in comparison to conventional fertilization, the deep placement method of applying lime nitrogen (LN) and urea fertilizer (DPF) increased the amount of nitrogen accumulated in soybean plants. As the plants developed, nitrogen fixation—a crucial mechanism for plant growth—improved, particularly with the deep application of slow-release lime nitrogen (LN) and urea fertilizer (DPF). These methods also resulted in the highest seed yield and were better than traditional methods. [11,15,28,45] supported these findings, showing that deep placement techniques using lime nitrogen (LN), or coated urea fertilizers had similar positive effects on soybean yields. The researchers concluded that

using mechanized machines to apply nitrogenous fertilizers deep into the soil improved soybean yields. In this study, delaying the supply of nitrogen positively affected the plant's health, leading to better seed yield, more pods, and higher seed production in the later stages of soybean growth.

5. Conclusion

Deep placement fertilizer stands out as a highly productive approach in soybean production, especially when combined with slow-release nitrogen and optimum timing. Its ability to enhance nodulation, nitrogen fixation, photosynthetic activity, and overall soybean yields underscores its importance in modern agricultural practices, promising a brighter future for soybean farmers aiming to maximize their crop productivity and quality. Deep placement of slow-release lime nitrogen (LN) and coated urea has proven to be beneficial compared to regular fertilization. This method involves placing seeds along with slow-release fertilizers 20 cm deep in the soil. By doing so, it delays the release of nitrogen until the later reproductive stages when soybeans require more nutrients for pod and seed formation. This new deep placement method, carried out using mechanized injectors, has advantages. It enhances nitrogen use efficiency and prevents the need for applying large amounts of fertilizers. Excessive fertilizer application can inhibit nitrogen fixation and nodule formation, reducing nitrogen availability for podding and seed formation during the reproductive stage, and resulting in lower soybean yields. In this study, the effect of deep placement of slow-release lime nitrogen calcium cyanamide, compost, and conventional fertilizer application on soybean seed yield, SPAD, height, and NDVI were investigated in a rainfed production system in two consecutive cropping seasons. Deep placement, compost, and conventional fertilizer technologies recorded yields of 2.7 tons/ha, 2.6 tons/ha, and 2.4 tons/ha respectively in the 2022 cropping season, while, for the 2023 cropping season deep placement combined with compost, deep placement, compost, and conventional recorded yield of, 1.31 tons/ha, 1.11 tons/ha, 1.1 tons/ha, and 0.98 tons/ha respectively. SPAD and NDVI were relatively higher in deep placement combined with compost and deep placement fertilizer technology as compared to compost and conventional methods for both cropping seasons of 2022 and 2023. Therefore, deep placement of slow–release lime nitrogen calcium cyanamide has the potential to be a sustainable farming technology to enhance yields in soybean cultivation.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org., Figure S1: Deep placement fertilizer applicator machine.

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