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The Impact of Using Different Types of Compost on the Growth and Yield of Corn

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Abstract: The cultivation of corn holds immense importance as a foundational global grain crop, catering to human sustenance and serving as vital animal feed. Moreover, corn plays a substantial role in biofuel production. Additionally, cultivating corn can have a positive effect on crop rotation by improving soil quality and reducing erosion. In a pot trial using six distinct compost variations derived from different organic wastes as fertilizers for GS210 corn, specific indices, such as Fv/Fm (0.80, 0.80, 0.81), Fv/F0 (4.07, 3.99, 4.03), PI (4.62, 4.22, 5.21), and RC/ABS (1.71, 1.68, 2.01), exhibited the highest values. Interestingly, mineral fertilization with NPK displayed significant benefits on various growth parameters like plant height (188.9 cm), cob length (17.50 cm), grains per cob (324.0), and thousand-grain weight (MTZ) (285.2). The difference in the cob grain count between NPK mineral fertilization and the control reached 168.5 grains, which was statistically confirmed. Furthermore, the grain's protein content notably increased with mineral fertilization (9.5) compared to the control (8.5). While organic fertilizers showed lower outcomes (9.1–9.3) than NPK mineral fertilization, they generally outperformed the control (8.5). This prompts the need for future studies to assess the effectiveness of individual organic fertilizers in combination with mineral nitrogen fertilization.

Keywords: *Zea mays*; organic fertilization; mineral fertilization; physiological measurements; plant growth

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1. Introduction

Sustainable development refers to a method that meets the needs of the present without compromising the ability of future generations to meet their own needs. It involves finding a balance between economic growth, social progress, and environmental protection to ensure that resources are used efficiently and that the well-being of both current and future societies is upheld. In the realm of sustainable agriculture, the quest for innovative fertilizers has intensified. With traditional organic and mineral fertilizers witnessing a steady rise in costs, researchers and practitioners are seeking viable alternatives that not only nourish crops but also align with environmental consciousness. One of the primary drivers behind this shift is the escalating expense associated with conventional fertilizers. Organic fertilizers, derived from natural sources, and mineral fertilizers, which involve chemical compounds, have long been the mainstay. However, their production costs have steadily increased, exerting financial strain on farmers and prompting exploration into more cost-effective alternatives. Managing generated waste appropriately is a significant concern in the contemporary world. Organic waste, for instance, can be recycled and repurposed, such as its utilization as a fertilizer. Numerous organic wastes, particularly those originating from agriculture, the food industry, kitchens, and even municipal sources, harbor valuable nutrients that are beneficial for crops. Thus, in agriculture, an effective approach involves implementing a closed-loop system, enabling the recycling of nutrients from organic waste as an alternative fertilizer [1]. However, it is important to note that the widespread adoption of such solutions might not always be feasible or justified in every scenario [2]. According to the findings by Bhatti et al. [3] and Strenner et al. [4], alternative organic fertilizers such as biogas fermentation residue, well-aged farmyard manure, both fresh and matured organic waste, green compost at various stages, and microbial carbonized compost can be effectively utilized. Oluwa et al.'s findings [5] suggest that employing organic fertilizers not only benefits the immediate crop but also has positive effects on subsequent crops within the rotation. This aspect should be considered in future agricultural research endeavors. Instances of excessive mineral fertilizer application in agriculture have been documented, presenting economic inefficiency and environmental risks [6]. Consequently, numerous countries are advocating solutions to diminish mineral fertilizer usage, advocating for alternatives, such as organic substitutes derived from diverse sources [7,8]. Several researchers [9–12] advocate for the synergistic utilization of mineral and organic fertilizers as a viable approach to curtail reliance on the former. Leaving crop residues, particularly straw, within fields is considered sound agricultural practice [13,14]. Berry et al. [15] corroborated the significance of crop residues as valuable fertilizers, emphasizing that nutrient availability hinges on the mineralization rate. Additionally, their broad C:N ratio necessitates consideration of the nutrient balance. Converting diverse organic wastes into biofertilizers stands out as an effective remedy, mitigating their detrimental environmental effects and cutting down on the quantities of mineral fertilizers employed [16,17]. Elias et al. [18] strongly supported the creation of soil fertility maps before determining crop fertilization needs. They demonstrated that, in corn cultivation, this approach led to elevated yields and decreased fertilization expenses. Past studies [19–22] underscore the pivotal role of understanding the soil nutrient content in providing precise fertilizer recommendations for all crops. Zhang et al. [22] and Sądej and Żołnowski [23] concluded that optimal fertilization profoundly impacts soil fertility, directly influencing both yields and their quality. In response to this perspective, Sądej et al. [24] emphasized that the results of fertilization depend on the soil type. Ocwa et al. [25] argued that elevating the intensity of fertilization should not be viewed as the primary agricultural technique for boosting crop yields. Their findings indicate that achieving optimal corn grain yield necessitates optimizing all agrotechnical practices and carefully selecting suitable varieties tailored to specific local habitat conditions.

Mącik et al. [26] highlight the necessity to shift the focus towards organic fertilizers and biopreparations, attributing this shift to the adverse shifts within agroecosystems caused by excessive mineral fertilizer usage. These actions align with the principles of fostering sustainable agriculture, resonating with initiatives like the European Green Deal in the European Union. Additionally, Sarajuoghi et al. [27] demonstrated the efficacy of biofertilizers and microbiological preparations in corn fertilization, emphasizing the importance of their more frequent utilization. Mącik et al. [19] advocated for the value of biofertilizers and biopreparations, especially within the framework of regenerative agriculture. Liu et al. [28] affirmed the advantages of utilizing organic waste in agriculture as a fertilizer, particularly in terms of carbon dioxide sequestration. Additionally, Gao et al. [29] and Shi et al. [30] substantiated how employing organic fertilizers enables a reduction in mineral fertilizer doses while concurrently achieving high corn yields with commendable grain quality.

Duan et al. [31] indicated that corn responds well to manure fertilization, which is a response not observed in wheat cultivation. On the contrary, Murmu et al. [32] found mineral fertilizers to be more effective in corn experiments compared to organic ones. Nevertheless, organic fertilizers significantly enhance the soil by enriching it with microorganisms, organic carbon, macroelements, and microelements, leading to a favorable environment for succeeding plants. Taj et al. [33] supported the positive impact of organic fertilizers on soils' physicochemical properties by increasing organic matter and improving the soil's pH. However, they recommend a balanced approach, suggesting the use of a combined dose of organic and mineral NPK fertilizers in appropriate proportions for corn cultivation. Pang and Letey [9] suggested that crops like corn, which have a substantial nitrogen requirement, show favorable responses to a combination of organic and mineral fertilization. Specifically, during certain developmental stages where the nitrogen demand is notably high, the application of mineral fertilizer becomes justified. Ahmad et al. [16] demonstrated through both pot and field experiments that employing organic fertilization alongside half the standard dose of mineral nitrogen is as effective as using the full nitrogen fertilizer dose (175 kg·ha^{-1}). This approach notably enhanced root mass, biomass, and, ultimately, corn grain yield.

Hu et al. [34] advocated for a combined approach to organic and mineral fertilization as a beneficial strategy for maize cultivation, recommending a ratio of 75% organic fertilizers to 25% mineral fertilizers. This blend aims to minimize greenhouse gas emissions while ensuring robust grain yields by bolstering soil fertility. Additionally, other scholars [35–38] underscore the importance of considering N_2O and CH_4 emissions when using organic fertilizers. Yao et al. [39] substantiated that leaving corn stalks in the field increased N_2O emissions. Conversely, He et al. [40], in their evaluation of various fertilization methods, found that an organic fertilizer resulted in the highest N_2O emissions when compared to chemical fertilization, chemical/organic combinations, and control groups without fertilization. Zhang et al. [22] highlighted that nitrogen losses were observed when fertilizers were applied either too early or too late in corn cultivation. Meanwhile, Asadu et al. [41] confirmed the efficacy of organic fertilizers derived from agricultural waste as a viable alternative to chemical fertilizers. Their study demonstrated the positive impact of bioorganic fertilizers on corn plant growth compared to the control group.

Sabourifard et al. [42] achieved the highest yield of corn seeds through the use of urea and vermicompost, whereas manure fertilization resulted in the highest content of oil and linolenic acid in the seeds. Numerous authors [43–45] advocate composting or vermicomposting, employing earthworms such as *Eisenia fetida* as the most effective means of managing organic waste. Patra et al. [43] investigated five distinct waste types—leaf litter (Tectona grandis), water hyacinth (*Eichhornia crassipes*), cauliflower waste (Brassica oleracea var. botrytis), coconut cores, and fungal waste—and found that vermicomposting demonstrated superior fertilizing properties compared to traditional composting. Maharjan et al. [46] and Rupani et al. [47] affirm the benefits of using earthworms in converting organic waste into vermicompost, although they note that this method may not always be universally efficient or applicable.

El-Hassanin et al. [48] and Rékási et al. [49] highlight limitations in using sewage sludge as a fertilizer due to the pathogenic microorganisms and heavy metals it contains, in line with international standards. However, they assert that with proper treatment and processing, sewage sludge can be transformed into a valuable and environmentally safe organic fertilizer. However, the implementation of sewage waste as a fertilizer is not without its considerations. Stringent guidelines and rigorous treatment processes are imperative to ensure the safety and efficacy of these fertilizers. Thorough treatment is crucial to eliminate pathogens and toxins, ensuring that the resulting product enhances crop growth without adverse effects on human health or the environment. The possibility of using sewage waste as a fertilizer presents a compelling opportunity to diversify and revolutionize agricultural practices. It is a prospect that not only offers a practical solution to rising fertilizer costs but also aligns with the global push toward sustainability and responsible resource management. Moreover, the shift towards sewage waste-derived fertilizers aligns with broader environmental goals.

Recycling waste into beneficial agricultural products reduces the strain on landfills and minimizes the environmental impact of waste disposal. It is a step towards a circular economy, where resources are repurposed, contributing to a more sustainable ecosystem. The transition from conventional fertilizers to sewage waste-derived alternatives is not an overnight transformation. It requires collaborative efforts among researchers, policymakers, waste management authorities, and farmers to establish protocols, conduct comprehensive studies, and facilitate adoption. The possibility of using sewage waste as a fertilizer presents a compelling opportunity to diversify and revolutionize agricultural practices. It is a prospect that not only offers a practical solution to rising fertilizer costs but also aligns with the global push toward sustainability and responsible resource management.

This study aimed to investigate how corn responds to fertilization using compost derived from different municipal waste sources compared to mineral fertilization NPK and a control group. The research hypothesis posited that organic fertilization could substitute NPK mineral fertilization without compromising the quantity and quality of grain yield.

2. Materials and Methods

2.1. Experimental Setup

To evaluate the impact of compost fertilization, we utilized two control samples. The first control sample consisted of soil without any added fertilizer; the second control sample involved mineral fertilization.

The soil was slightly acidic (pH 1N KCl 6.1), the content of phosphorus and magnesium was average (P_2O_5 14.8 mg·kg^{-1} d.m., Mg 6.2 mg·kg^{-1} d.m.), and the potassium content was high (21.4 K_2O mg·kg^{-1} d.m.). The content of microelements was average (Zn 10.7 mg·kg^{-1} d.m., Cu 5.22 mg·kg^{-1} d.m., Fe 2248 mg·kg^{-1} d.m., Mn 409 mg·kg^{-1} d.m.).

The second control sample involved mineral fertilization, using Polifoska®8 (8% N, 24% P_2O_5, 24% K_2O) and Pulrea + INu (46% N). Calculated doses of NPK mineral fertilizers—100 kg·ha^{-1} N, 96 kg·ha^{-1} P_2O_5, and 96 kg·ha^{-1} K_2O—were applied per pot before sowing. Additionally, a 50 kg·ha^{-1} N application occurred during the four-leaf phase, mirroring the common practice of NPK mineral fertilization in the research area.

Compost fertilization utilized the substrate generated in the experiment, as detailed by Zapałowska et al. [50]. The mentioned compost was prepared using different types of municipal waste in various mass proportions (kg by mass):

Compost 1: sewage sludge (165 kg) + sawdust (35 kg);
Compost 2: sewage sludge (90 kg) + sawdust (10 kg) + garden and park waste (100 kg);
Compost 3: garden and park waste (180 kg) + sawdust (20 kg);
Compost 4: sewage sludge (165 kg) + sawdust (35 kg) + earthworms;
Compost 5: sewage sludge (90 kg) + sawdust (10 kg) + garden and park waste (100 kg) + earthworms;
Compost 6: garden and park waste (180 kg) + sawdust (20 kg) + earthworms.

The municipal waste was distributed among six bioreactors, each with a thermally insulated plastic cube holding 1 m^3. To aid the bioconversion process, mechanical mixing was necessary. Weekly checks tracked the moisture level of the composting organic material. Temperature readings highlighted four key stages in the composting process.

In our experiment, the setup was as follows:

- A-Soil without any fertilizer;
- B-Soil + Polifoska®8 + Pulrea + INu;
- C-Soil + Compost 1: sewage sludge (165 kg) + sawdust (35 kg);
- D-Soil + Compost 2: sewage sludge (90 kg) + sawdust (10 kg) + garden and park waste (100 kg);
- E-Soil + Compost 3: garden and park waste (180 kg) + sawdust (20 kg);
- F-Soil + Compost 4: sewage sludge (165 kg) + sawdust (35 kg) + earthworms;
- G-Soil + Compost 5: sewage sludge (90 kg) + sawdust (10 kg) + garden and park waste (100 kg) + earthworms;
- H-Soil + Compost 6: garden and park waste (180 kg) + sawdust (20 kg) + earthworms.

The trial was conducted with a single factor across four repetitions. The tested factor was organic fertilization (variants C, D, E, F, G, and H) compared to the control (A) and (B).

2.2. Chemical Analyses of Compost

The compost was subjected to chemical analysis in accordance with the methodologies specified in the publication by Zapałowska et al. [51]. The levels of microelements were measured using the absorption spectrometric method. The available phosphorus and potassium were estimated using the Egnér–Riehm method. The total organic carbon and nitrogen content was determined using the dry combustion method.

2.3. Seed Material

In the experiment, the seed of the GS210 corn variety (Agro Seed Sp. z o. o., Brzezie, Poland) was used. The seeds were initially treated with the following two active substances: metalaxyl and prothioconazole.

2.4. Experimental Design

The plastic pots employed had a capacity of 20 L and a 30 cm diameter. The soil chosen was Haplic Cambisol-Cmha [IUSS 2015], obtained from a field located at the Experimental Department of the University of Rzeszów in Krasne, near Rzeszów, Poland. The initial application of NPK mineral fertilizers before sowing was calculated at 100 $kg \cdot ha^{-1}$ of N, 96 $kg \cdot ha^{-1}$ of P_2O_5, and 96 $kg \cdot ha^{-1}$ of K_2O per pot. Moreover, an extra 50 $kg \cdot ha^{-1}$ of N was administered during the four-leaf phase. This method corresponds with the conventional technique for NPK mineral fertilization in the research area. The doses of compost (C-H) per pot were calculated to provide 150 $kg \cdot ha^{-1}$ of nitrogen. The remaining elements were not equilibrated, assuming their contribution would enrich the soil's fertility—a factor slated for assessment in upcoming experiments.

Corn seeds were planted on 5 April 2023, with three seeds per pot. Subsequently, these pots were placed within growth chambers (Model GC-300/1000; JEIO Tech Co., Ltd., Seoul, Korea) at a temperature of 20 ± 1 °C, with a relative humidity of 60 ± 3%. The photoperiod was maintained at 16/8 h (L/D), with a maximum light intensity of around 300 $\mu mol\ m^{-2}\ s^{-1}$ during the day. The substrate moisture level was sustained at 60% of the field water capacity. Pot placements were randomly altered every 5 days. The stages of corn development were tracked following the BBCH scale (Bundesanstalt, Bundessortenamtund CHemische Industrie) [52]. During the one-leaf phase (11 BBCH), one plant was retained per pot. Upon reaching the four-leaf stage (14 BBCH), the pots were relocated to a vegetation hall with natural light and a constant temperature of 20 ± 1 °C. Soil moisture was sustained at 60% of the field water capacity throughout this phase. The experiment persisted until full maturity (89 BBCH), at which point the plants were harvested, and biometric measurements, including plant height, cob length, the number of grains per cob, and thousand-grain weight (MTZ), were recorded. The plant's growth and development phase spanned 178 days, measured from the day of sowing until the day of harvesting. Additionally, the total protein content in the harvested grain was assessed using the Kjeldahl method [53].

2.5. Chlorophyll Fluorescence

Leaf chlorophyll fluorescence measurements were conducted using a handheld Pocket PEA instrument (Hansatech Instruments, King's Lynn, Norfolk, UK). A black shading clip was affixed to the upper (apical) leaf of each plant during the fifth leaf stage (15 BBCH). After a 30 min interval, measurements were taken for the maximum quantum yield of photosystem II (PSII) (Fv/Fm), the maximum quantum yield of primary photochemistry (Fv/F0), and the photosynthetic efficiency index (PI).

2.6. Measurement of Gas Exchange

The LC pro-SD photosynthesis measurement system (ADC Bioscientific Ltd., Herts, UK) was used for the measurements. The net photosynthetic rate (PN, mmol (CO_2) $m^{-2} \cdot s^{-1}$), transpiration rate (E, mmol $m^{-2} \cdot s^{-1}$), stomatal conductance (gs, mmol H_2O $m^{-2} \cdot s^{-1}$), and intercellular CO_2 concentration (Ci, mol CO_2 $m^{-2} \cdot s^{-1}$) were measured on four fully expanded leaves in every pot. The flow accuracy of the LCpro-SD plant leaf photosynthesis measurement chamber was ±2% of its range. During the measurement, the light intensity was 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$, and the temperature in the measurement chamber was 21 °C.

2.7. Soil Plant Analysis Development

The relative chlorophyll content was measured using a Minolta SPAD-502 chlorophyll meter (Konica Minolta, Inc., Tokyo, Japan) and expressed in unmeasured SPAD–Soil Plant Analyses Development–units, the value of which was closely related to chlorophyll content. The SPAD was measured three on each pot on the upper fully developed leaves. These measurements were taken at the five-leaf stage (15 BBCH), the third-leaf stage (33 BBCH), and the flowering stage (65 BBCH).

2.8. Statistical Analyses

Statistical analysis was performed using the TIBCO Statistica 13.3.0 (TIBCO Software Inc., Palo Alto, CA, USA) program. One-way ANOVA was applied; Tukey's post hoc test ($p \leq 0.05$) was used to determine the significance of differences between the mean values of the studied parameters.

3. Results

3.1. Compost Properties

The properties of the compost utilized in the experiment differed based on the compost type. The pH values of the resulting substrates ranged between 5.8 and 8.1. Compost 4 displayed the lowest values, while compost 6 exhibited the highest, as illustrated in Table 1. Of all the compost variants examined, compost 1 displayed the highest average nitrogen (N) content. Compost 3 exhibited the highest carbon-to-nitrogen (C:N) ratio at 37.72%, whereas compost 1 demonstrated the lowest C:N ratio at 19.25%. The P_2O_5 content varied from 13.00 g·kg^{-1} (compost 1) to 1.09 g·kg^{-1} (compost 2) on average. Composts 2, 5, and 6 exhibited the highest potassium (K_2O) levels, measuring 6.88 g·kg^{-1}, 7.63 g·kg^{-1}, and 7.28 g·kg^{-1}, respectively. Among the analyzed variants, compost 1 presented the highest concentration of lead (Pb), whereas compost 6 exhibited the highest concentrations of chromium (Cr) and nickel (Ni).

Table 1. The chemical properties of compost used. Results are expressed as the mean value ± standard deviations. Different letters a, b, c, d, e indicate significant differences, $p < 0.05$.

Parameter	Compost Variants					
	Compost 1	Compost 2	Compost 3	Compost 4	Compost 5	Compost 6
pH in KCl	5.9c	6.3c	7.1b	5.8c	7.1b	8.1a
Dry matter (%)	27.6d	35.7c	55.5a	26.3d	35.8c	44.9b
N (%)	4.02 ± 0.32a	1.82 ± 0.14c	1.01 ± 0.08d	2.59 ± 0.20b	1.86 ± 0.14c	1.56 ± 0.12cd
P_2O_5 (g·kg^{-1} d.m.)	13.00 ± 1.04a	1.09 ± 0.01d	2.01 ± 0.16cd	9.42 ± 0.75b	8.89 ± 0.71b	3.64 ± 0.29c
K_2O_5 (g·kg^{-1} d.m.)	4.93 ± 0.30bc	6.88 ± 0.55ab	4.63 ± 0.37c	5.09 ± 0.40b	7.63 ± 0.61a	7.28 ± 0.58a
C:N (%)	19.25 ± 0.91d	23.57 ± 0.86c	37.72 ± 0.54a	28.06 ± 0.42b	21.29 ± 0.38cd	30.32 ± 0.19b
Mg (%)	0.32 ± 0.03b	0.32 ± 0.03b	0.20 ± 0.00b	0.34 ± 0.03b	0.3 ± 0.03b	0.51 ± 0.02a
Ca (%)	1.7 ± 0.11bc	1.52 ± 0.09c	1.95 ± 0.08b	2.13 ± 0.02ab	1.64 ± 0.15c	2.34 ± 0.14a
Pb (mg·kg^{-1} d.m.)	10.0 ± 0.8a	<8.0a	<8.0a	<8.0a	<8.0a	<8.0a
Cr (mg·kg^{-1} d.m.)	<10c	<10c	12.0 ± 0.96b	12.0 ± 0.93b	11.0 ± 0.90b	23.0 ± 1.84a
Cu (mg·kg^{-1} d.m.)	70.0 ± 5.6b	58.0 ± 4.64c	16.0 ± 1.28e	84.0 ± 6.72a	45.0 ± 3.6d	16.0 ± 1.28e
Ni (mg·kg^{-1} d.m.)	<5.0b	<5.0b	5.3 ± 0.42b	<5.0b	5.1 ± 0.40b	11.0 ± 0.88a
Cd (mg·kg^{-1} d.m.)	0.44 ± 0.03ab	0.42 ± 0.03ab	0.34 ± 0.03b	0.5 ± 0.05a	0.38 ± 0.03b	0.35 ± 0.03b
Zn (mg·kg^{-1} d.m.)	253 ± 20.2b	223 ± 17.8c	91.0 ± 7.28d	274 ± 21.91a	232 ± 18.56c	78.0 ± 6.24e
Hg (mg·kg^{-1} d.m.)	0.132 ± 0.01b	0.104 ± 0.01c	0.026 ± 0.01d	0.18 ± 0.01a	0.066 ± 0.01d	0.042 ± 0.01d

3.2. Relative Content of Chlorophyll

The differences in the plant's nutritional condition, assessed in SPAD units (Figure 1), exhibited significant variability among various fertilization approaches. During the initial assessment (15 BBCH), the SPAD index was notably highest with NPK mineral fertilization and organic variants C, D, and F, while the control displayed considerably lower readings. The SPAD readings for fertilizers E, G, and H did not show significant differences compared to the control. In the second assessment, plants fertilized with NPK minerals exhibited the best nourishment, followed by C and F variants, which also showed positive outcomes. By the third measurement, plants treated with NPK minerals alongside the variants C, D, and F displayed the most nourished state.

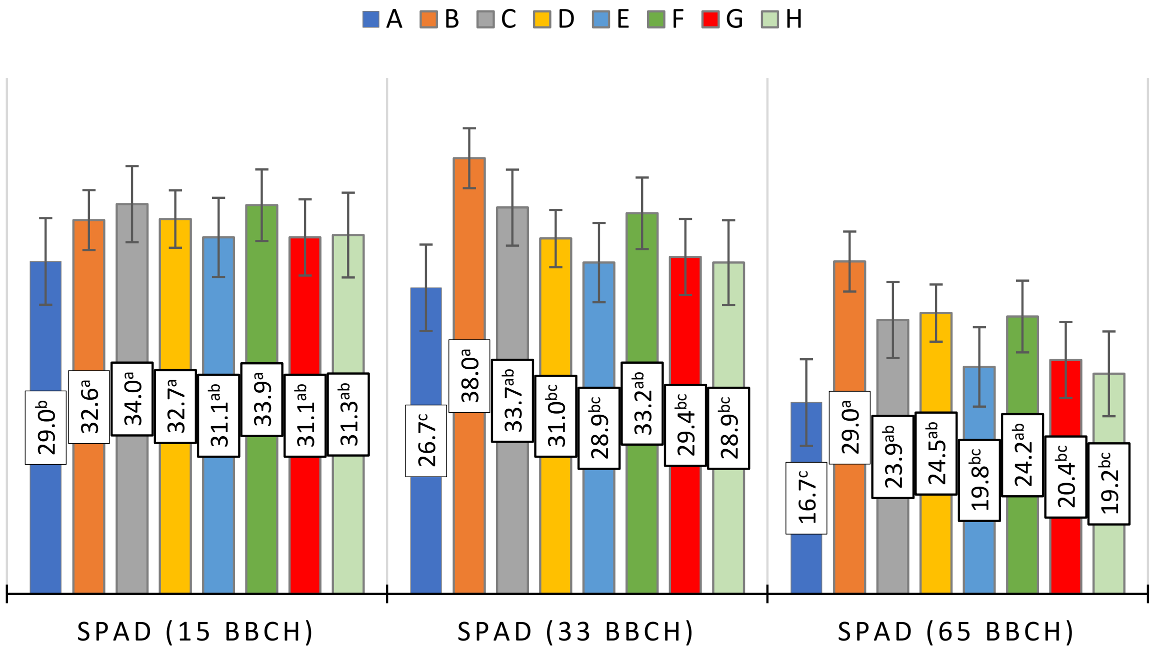

Figure 1. Soil Plant Analysis Development (SPAD). A, B, C, D, E, F, G, H—different variant fertilizers (n = 4). Different letters in the columns indicate significant differences ($p < 0.05$) according to the analysis of variance (ANOVA). The standard error is marked on the columns.

3.3. Chlorophyll Fluorescence

The Fv/Fm, representing the maximum photochemical efficiency of PSII, showed higher values following the application of NPK mineral fertilization, along with fertilization using variants D and F, compared to the control. The introduction of the C variant showed a positive effect on the Fv/Fm measurement, yet the variance from the control was considered negligible. Moreover, the measurement of the maximum quantum yield of primary photochemistry (Fv/F0) indicated the most favorable outcomes with NPK mineral fertilization and the variants C, D, and F. Conversely, significantly lower outcomes were noted in the control (A) and when employing variants E, G, and H.

The Performance Index (PI) reached its peak post the application of variant F, while variant C also displayed relatively high PI measurements compared to the control (A). As for the total number of active reaction centers for absorption (RC/ABS), its highest values were noted following the use of the F variant, significantly diverging from the lower values recorded in the control (A) (Table 2).

3.4. Gas Exchange

Leaf stomatal conductance (Gs) and transpiration rates (E) remained largely unaffected across the different variants compared to the control. Remarkably, the application of the D variant displayed a trend toward enhancing both parameters, though falling within the bounds of statistical error. However, the measurement of the intercellular CO_2 concentration (CI) showed a significant increase, registering its highest levels in the control (188.0 µmol (CO_2) mmol^{-1}) and following only NPK mineral fertilization (188.0 µmol (CO_2) mmol^{-1}). Contrastingly, significantly lower CI readings were recorded after adding the variants C, D, F, G, and H. Regarding the net photosynthesis intensity (PN), variant D resulted in the highest values (19.8 μmol $(CO_2)\cdot m^{-2}s^{-1}$), while the application of the NPK mineral fertilization (10.8 μmol $(CO_2)\cdot m^{-2}s^{-1}$) led to the lowest PN levels (Table 3).

Table 2. Plant physiological measurements. Results are expressed as the mean value ± standard deviations, (n = 4). Different letters in the same column indicate significant differences, $p < 0.05$.

Variant	Fv/Fm (Maximal Photochemical Efficiency of PSII)	Fv/F0 (Maximum Quantum Yield of Primary Photochemistry)	PI (Performance Index)	RC/ABS (Total Numer of Active Reaction Centes for Absorbtion)
A	0.78 ± 0.002b	3.74 ± 0.05b	3.11 ± 0.87d	1.45 ± 0.25b
B	0.82 ± 0.006a	4.05 ± 0.14a	4.37 ± 0.94b	1.77 ± 0.26ab
C	0.80 ± 0.007ab	4.07 ± 0.17a	4.62 ± 2.05ab	1.71 ± 0.53ab
D	0.81 ± 0.003a	3.99 ± 0.07a	4.22 ± 0.89b	1.68 ± 0.24ab
E	0.77 ± 0.009b	3.70 ± 0.28b	3.68 ± 1.18cd	1.74 ± 0.34ab
F	0.81 ± 0.009a	4.03 ± 0.30a	5.21 ± 1.64a	2.01 ± 0.41a
G	0.78 ± 0.007b	3.77 ± 0.20b	3.88 ± 1.75bc	1.64 ± 0.49ab
H	0.77 ± 0.009b	3.76 ± 0.21b	3.37 ± 1.42cd	1.54 ± 0.39ab

3.5. Biometric Parameters of Plants

NPK mineral fertilization (B) led to increased corn plant height (188.9 cm), with similarly tall plants observed after using C, D, and F variants. Variants E, G, and H resulted in shorter plants, while the control exhibited the shortest plants (132.9 cm), which is a distinction supported by statistical analysis. The influence of the variants used extended to cob length, with the longest cobs resulting from NPK mineral fertilization (17.5 cm), notably shorter ones observed after applying the variants E and H (respectively 13.63 and 13.25 cm), as well as in the control group (11.5 cm). There were considerable variations in grain count within the cob; the highest count was noted after NPK mineral fertilization (324 pieces), with significant numbers also seen following the use of variants D and F (302.3 and 273.1 pieces, respectively) compared to the control (155.5 pieces). The difference in cob grain count between NPK mineral fertilization and the control reached 168.5 grains, which was statistically confirmed. Furthermore, the thousand-grain weight reached its peak after NPK mineral fertilizer (285.2 g) application and with variant D (276.6), markedly distinct from variants C, E, F, G, H, and the control (248.1) (Table 4).

Table 3. Plant physiological measurements, cont. Different letters a, b, c, d, e indicate significant differences, $p < 0.05$.

Variant	Gs (Stomatal Conductance, mmlo $(H_2O)\cdot m^{-2}s^{-1}$)	E (Transpiration Rate, mmlo $(H_2O)\cdot m^{-2}s^{-1}$)	CI (Intercellular CO_2 Concentration, μmol (CO_2) mmol^{-1})	PN (Net Photosynthetic Rate, μmol $(CO_2)\cdot m^{-2}s^{-1}$)
A	0.11 ± 0.03a	1.65 ± 0.25a	188.0 ± 15.3a	12.1 ± 2.61bc
B	0.10 ± 0.09a	1.39 ± 0.84a	183.0 ± 45.3a	10.8 ± 7.84c
C	0.08 ± 0.02a	1.27 ± 0.24a	139.0 ± 39.9de	11.5 ± 1.01bc
D	0.16 ± 0.08a	2.05 ± 0.73a	133.5 ± 34.7e	19.8 ± 5.88a
E	0.13 ± 0.02a	1.93 ± 0.18a	168.5 ± 15.2ab	15.3 ± 1.65ab
F	0.10 ± 0.02a	1.62 ± 0.16a	163.2 ± 24.9bc	13.1 ± 2.76bc
G	0.13 ± 0.01a	1.95 ± 0.08a	152.0 ± 20.9cd	16.7 ± 1.82ab
H	0.13 ± 0.01a	1.91 ± 0.09a	147.0 ± 11.7cd	16.4 ± 1.19ab

Table 4. The chosen biometric measurements of corn plants. Results are expressed as the mean value ± standard deviations, (n = 4). Different letters in the same column indicate significant differences, $p < 0.05$.

Variant	Plant Height (cm)	Length of Cob (cm)	Number of Grains in the Cob	Thousand Grain Weight (g)
A	132.9 ± 13.91c	11.50 ± 0.58c	155.5 ± 56.1c	248.1 ± 6.52e
B	188.9 ± 14.58a	17.50 ± 0.58a	324.0 ± 51.6a	285.2 ± 3.48a
C	168.5 ± 7.12ab	15.75 ± 1.89ab	266.0 ± 44.1b	273.5 ± 3.52bc
D	174.5 ± 11.13ab	15.50 ± 1.29ab	302.3 ± 27.3ab	276.6 ± 2.22ab
E	160.1 ± 9.76b	13.63 ± 1.25b	221.0 ± 60.6b	264.9 ± 5.04cd
F	167.4 ± 11.41ab	14.75 ± 1.50ab	273.1 ± 60.7ab	274.6 ± 2.94b
G	160.2 ± 10.59b	14.00 ± 2.16ab	200.3 ± 29.8bc	264.6 ± 3.39cd
H	161.8 ± 10.80b	13.25 ± 1.89b	254.5 ± 45.8b	261.8 ± 2.42d

3.6. Plant Dry Weight and Grain Yield per Plant

The highest straw dry weight per individual plant was observed following mineral fertilization with NPK (B) and variant D (Figure 2). Variants C and F resulted in notably lower straw weights. Following fertilization with variants E, G, and H, the straw weight stayed consistently low, with the lowest recorded in the control (A). The difference in straw dry weight per individual plant between variants B and C, in comparison to the control (A), amounted to 88.7 and 76.3 g, respectively. Regarding the grain yield per individual plant, significant differences were noted among the various fertilization methods (Figure 2). NPK mineral fertilization (B) exhibited the most favorable effect on this parameter. A comparable grain weight per plant was observed after applying fertilizer D, although significantly lower yields were evident with the remaining variants, particularly E and G. The plants in the control group (A) produced the lowest grain weight. The difference in grain weight per individual plant between variants B and D, in contrast to the control (A), was recorded at 54.3 and 45.3 g, respectively.

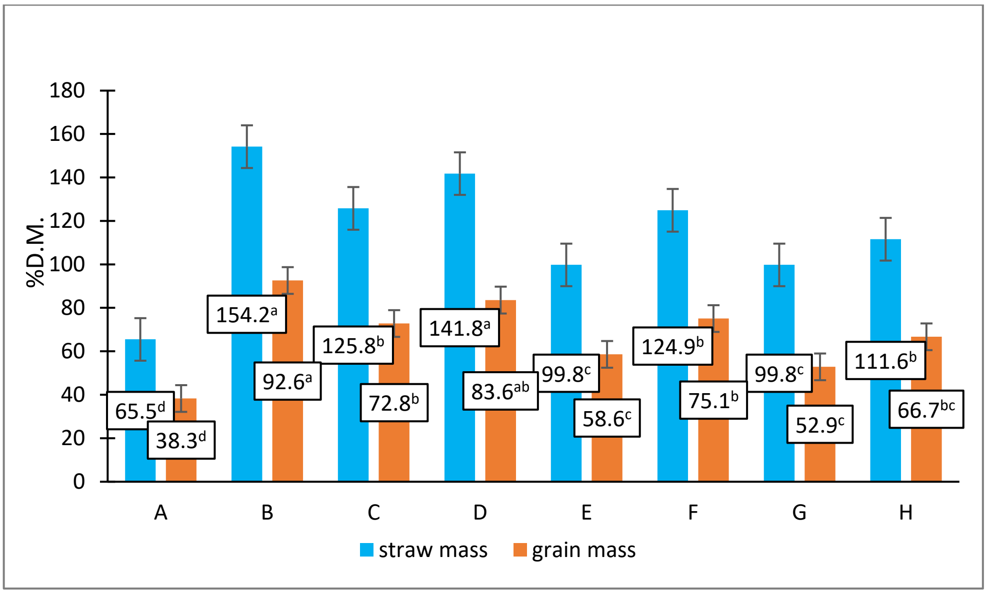

Figure 2. Dry mass of straw and grain from the plant. A, B, C, D, E, F, G, H—variant fertilizer, (n = 4). Different letters in the columns indicate significant differences ($p < 0.05$) according to the analysis of variance (ANOVA). The standard error is marked on the columns.

3.7. Protein Content in Grain

The grain protein content notably increased after mineral or organic fertilization in comparison to the control. The results across individual fertilization variants (B–H) consistently exceeded 9% dry matter (D.M.). Contrastingly, the protein content in the control seeds stood at only 8.5% D.M. (Figure 3).

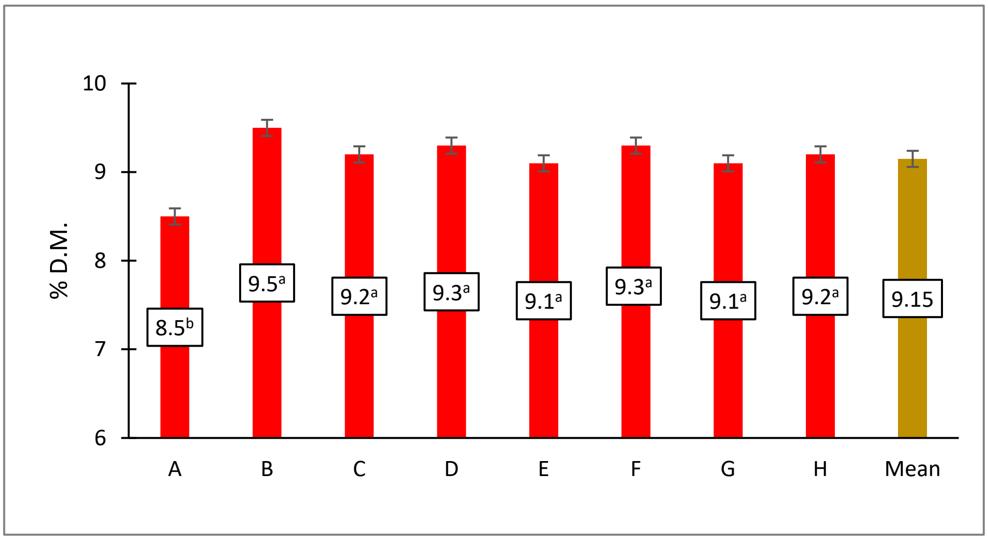

Figure 3. Total protein content in grain. A, B, C, D, E, F, G, H—variant fertilizer, (n = 4). Different letters in the columns indicate significant differences ($p < 0.05$) according to the analysis of variance (ANOVA). The standard error is marked on the columns.

4. Discussion

Modern agriculture places significant emphasis on adopting eco-friendly agrotechnical practices to concurrently improve field crop efficiency [29]. This urgency arises from the necessity to increase global food production in the upcoming years while mitigating negative impacts on the natural environment. Therefore, promoting practices like closed-loop systems in agriculture becomes significant, allowing for the recycling of organic waste. This approach enables the retrieval of a considerable quantity of nutrients, particularly nitrogen, while simultaneously cutting down on agricultural production expenses [54]. The ongoing industrialization, urbanization, and transformation in rural landscapes contribute to a continual surge in generated waste that requires thoughtful management. Converting organic waste into fertilizers stands out as one of the most effective solutions for managing such organic waste [55].

Our study assessed the viability of using various composted organic waste materials to fertilize corn, comparing their effectiveness against NPK mineral fertilization and a control group devoid of any fertilization (Table 1). The assessments of plant nutritional status, as indicated by SPAD units, unveiled significant differences among the various fertilization variants (Figure 1). Mineral (B) and organic fertilization in variants C and F exhibited the most positive impact on the SPAD index across all three measurements. However, variant D also yielded promising results in the initial and final measurements. Conversely, SPAD index readings following fertilization with variants E, G, and H did not significantly differ from the control, indicating their comparatively lower efficacy.

De Morais et al. [56] affirmed the varied release rates of nutrients from organic fertilizers, emphasizing the need to consider this factor post-application. Costa et al. [57] asserted the reliability, speed, and non-destructive nature of the SPAD chlorophyll meter in gauging plant nutritional status. Their research indicates a direct rise in SPAD meter readings with increasing nitrogen fertilizer dosage, although the correlation coefficient between SPAD readings and grain yield showed a moderately positive relationship. Szulc et al. [58] corroborated the efficacy of SPAD measurements in evaluating the efficiency of applied agrotechnical treatments, particularly nitrogen fertilization. Uddin et al. [59] noted that nitrogen fertilization elevates the chlorophyll content in corn leaves, resulting in significant enhancements in yield components, overall yield, and grain quality. Rostami et al. [60] confirmed that the use of biofertilizers notably amplifies the chlorophyll content and other biometric parameters in plants. However, they observed a substantial decline in the chlorophyll index with increased cadmium contamination levels in the soil.

Chlorophyll fluorescence assessments revealed the higher maximum photochemical efficiency of PSII (Fv/Fm) following NPK mineral fertilization and variants D and F compared to the control. The maximum quantum yield of primary photochemistry (Fv/F0) was notably influenced by NPK mineral fertilization and variants C, D, and F. Variants F and C showcased the highest Performance Index (PI) readings, while the total number of active reaction centers for absorption (RC/ABS) peaked post-F fertilization (Table 2).

Maxwell et al. [61] highlighted chlorophyll fluorescence analysis as one of the most widely used techniques among plant physiologists and ecophysiologists. It proves particularly valuable in evaluating crop conditions subjected to diverse agrotechnical treatments, such as fertilization. Force et al. [62] affirmed the versatile applications of chlorophyll fluorescence measurements, spanning from fundamental photosynthesis assessments to evaluating plant responses to environmental stressors or overall plant health (Table 3). Li et al. [63] demonstrated the adverse impact of nitrogen deficiency on photosynthetic parameters and chlorophyll fluorescence (Fv/Fm, Fv/Fo) in corn plants. They further established a significant correlation between the measured parameters of plant photosynthesis and the resulting grain yield.

Fertilization using variant D resulted in increased measurements of leaf stomatal conductance (Gs) and transpiration rate (E), although it fell within the margin of statistical error when compared to the control. The intercellular CO_2 concentration (CI) was notably highest in the control and following NPK mineral fertilization. Net photosynthesis intensity (PN) peaked during the post-application of variant D, while its lowest point was registered after NPK mineral fertilization (B). Li et al. [63] provided evidence demonstrating that nitrogen fertilization enhanced leaf stomatal conductance (Gs) parameters during the corn grain filling stage.

In our study, the most impressive results, with the tallest plants averaging 188.9 cm, the longest cobs measuring 17.5 cm, and the highest grain count per cob at 324.0, emerged following NPK mineral fertilization (Table 4). The difference in cob grain count between NPK mineral fertilization and the control amounted to 168.5 grains. Moreover, the thousand-grain weight peaked after applying the NPK mineral fertilizer and variant D, standing out from variants C, E, F, G, H, and the control.

Muniswami et al. [64] highlighted the use of various alternative fertilizers and microorganisms in crop production, showcasing their effectiveness, especially in terms of plant morphology, yield, and grain quality in corn. Shinde Madhumati et al. [65] supported this by confirming the positive modification of corn parameters under organic fertilization, particularly when combining biofertilizers with bacteria like Azotobacter and Phosphate-Solubilizing Bacteria. Amanolahi-Baharvand et al. [66] and Ajami [67] underscored the significant impact of combining organic and mineral fertilization on corn yield components, surpassing the effects of singular applications. Yessoufou et al. [68] advocated for the optimal variant in corn cultivation, using the full dose of manure alongside half the recommended dose of mineral fertilizer. De Morais et al. [56] suggested supplementing slow-releasing organic fertilizers with additional mineral fertilization to boost corn biomass. Wu et al. [69] highlighted the conversion of organic waste into fertilizer via black soldier fly larvae (BSFL), noting its positive impact on photosynthetic parameters and the overall biomass of corn plants and roots. Furthermore, multiple authors [39–41] advocated composting or vermicomposting organic waste, utilizing earthworms like *Eisenia fetida*, as a beneficial approach to managing organic waste.

The highest individual plant straw dry weight was achieved through NPK mineral fertilization and variant D (Figure 2). In contrast, variants C, E, F, G, and H exhibited significantly lower straw weights, while the control, as expected, displayed the lowest straw weight due to the absence of fertilization. The difference in dry straw weight per individual plant between variants B and C, compared to the control (A), stood at 88.7 and 76.3 g, respectively.

de Matos Nascimento et al. [70] advocated for biofertilizers as a valuable nutrient source for corn, suggesting their potential to replace up to 22% of the mineral nitrogen fertilizer when appropriately utilized. Their research also highlighted the capacity of biofertilizers to enhance plant biomass while reducing cultivation costs. Liang et al. [71] observed that top dressing with a bio-gas slurry and substituting the chemical fertilizer prolonged the plants' greenness, thereby extending their vegetation period. The grain weight per individual plant displayed significant variation across the evaluated fertilization variants (Figure 2). NPK mineral fertilization emerged as the most advantageous in terms of this parameter. While fertilizer D resulted in comparable grain weight per plant, the remaining variants, particularly E and G, exhibited significantly lower yields. The control plants yielded the lowest grain weight. The difference in grain weight per individual plant between variants B and D, compared to the control (A), amounted to 54.3 and 45.3 g, respectively.

Xin et al. [72] demonstrated that utilizing solely optimal doses of mineral fertilizer enhanced yields and efficiently utilized ingredients like phosphorus. However, they suggested that replacing a portion of chemical fertilizers with organic alternatives might be promising, contingent upon the cultivated species. In their experiments, combined mineral and organic fertilization yielded superior results in corn compared to wheat. Buligon et al. [73] advocated for biofertilizers, affirming their capacity to completely (100%) or partially (50%) substitute synthetic N fertilizers without compromising yield. They also found no significant impact on corn plant growth and development based on the method of biofertilizer application, whether in soil or as a foliar application. Naeem et al. [17] highlighted the potential of processing local organic waste into a fertilizer. They found optimal results through the combined use of organic and mineral fertilization, particularly in balanced proportions, yielding high crop yields while minimizing environmental impacts. Dineshkumar et al. [74] noted the positive impact of marine algae on seed germination and initial plant growth in corn cultivation. However, they found that a blend of cow manure and marine algae had the most advantageous effect on corn yield. Liu et al. [75] emphasized the multifaceted nature of fertilization effectiveness, affected by factors like soil quality and agrotechnical treatments such as forecrop or tillage. Yang et al. [76] suggested that while the effects of fertilization, including organic methods, yield reliable results, their full impact manifests in long-term field experiments. The excessive incorporation of inorganic fertilizers into the soil was cautioned against as poor agricultural practice. Zhai et al. [77] emphasized considering not just crop yield but also economic and ecological impacts while assessing the effects of fertilization. Zhang et al. [22] showcased how corn yield, after employing combined mineral and organic fertilizers, increased significantly (from 27.76% to 68.01%) compared to the control, contingent upon the specific fertilization variant used.

The protein content in corn grain significantly increased following NPK mineral fertilization or organic fertilization across all variants compared to the control, where the grain protein content stood at only 8.5% D.M. (Figure 3).

Fadlalla et al. [78] and Abd El-Gawad et al. [79] demonstrated that both mineral and organic fertilization not only improved corn yield but also enhanced the quality of the grain, particularly its protein content. Hu et al. [80] and Uddin et al. [59] further confirmed the positive impact of fertilization, including organic methods, on elevating the protein content in corn grain. They cautioned about the variation in nitrogen use from different fertilizers, emphasizing the need for careful planning in corn fertilization practices. Sabourifard et al. [42] highlighted the influence of FYM manure (200 kg $N \cdot ha^{-1}$) on increasing the oil and linolenic acid content in corn grain. Additionally, they found the highest oil yield post-fertilization with urea and vermicompost. He et al. [81] raised concerns regarding the heavy metal content in certain fertilizers, especially unconventional ones. They underscored the importance of preventing soil and grain contamination with heavy metals in such scenarios.

Over-fertilization can lead to nitrogen loss, posing a risk in agricultural practices [4]. Comparatively, mineral and organic fertilization differ notably in the duration of nitrogen availability in plants. Studies have shown that applying 5 tons ha^{-1} of compost significantly increases maize productivity, enhancing both yield and yield components. Regarding nitrogen application, utilizing 130 $kg \cdot ha^{-1}$ has displayed better results compared to 65 kg $N \cdot ha^{-1}$. Splitting the nitrogen application, with half at sowing and half at the knee stage, notably boosts maize productivity. Therefore, for general maize cultivation, combining 5 tons ha^{-1} of compost with 130 kg of $N \cdot ha^{-1}$, split between sowing and the knee stage, is recommended [82].

The combination of compost with inorganic fertilizer at rates of 5 tons/ha alongside 50 kg urea/ha and 100 kg of diammonium phosphate/ha tends to yield better maize growth and higher yields compared to using only an inorganic fertilizer. Moreover, it contributes to the sustainable enhancement of the soil's physico-chemical properties [83].

Organic material amendments in plots have shown enhanced emergence rates and improved growth properties in maize [84].

Research by Zhang et al. [85] has demonstrated that replacing 30% of N fertilizer with compost is an effective nutrient management strategy. It maintains N uptake and the yield of maize while reducing N loss and increasing soil fertility.

Studies have indicated that organic fertilizers can enhance the initial growth of corn, improving parameters like plant height, stem diameter, leaf count, and corn dry weight, comparable to chemical fertilizers. They also elevate chlorophyll levels and the leaf nitrogen content in corn, suggesting the potential of manure and compost as efficient nutrient sources for corn cultivation, potentially replacing chemical nitrogen fertilizers. Additionally, a SPAD meter has been proven effective in identifying soil nitrogen deficiencies [86].

Olowoake et al. [87] suggested that utilizing fertilizer CJ at a rate of 2.5 t/ha not only enhances soil productivity but also results in higher maize yields compared to using NPK 15–15–15 at 60 kg N/ha.

In the research conducted by Jiagwe [88], maize yield significantly increased with various fertilizer applications—DAP, vermicompost, shaded stored manure, open-air stored manure, and cattle manure slurry—at identical nitrogen rates. All methods proved economically viable, with vermicompost standing out as the most financially sensible option. Furthermore, vermicomposting is an environmentally friendly technology known to reduce gaseous emissions and retain nutrients within cattle manure.

Supplementing with compost and NPK fertilizer notably enhanced the growth and yield metrics for maize. Parameters such as plant height (up to 26%), the number of leaves per plant (up to 20%), stem girth (up to 22%), and fresh maize fodder weight (up to 25%) exhibited significant increases. Additionally, concentrations of key macronutrients in maize leaves, such as nitrogen (up to 46%), phosphorus (up to 27%), and potassium (up to 38%), were notably elevated compared to the control. However, variations in phosphorus concentration within the maize leaves were observed among different compost treatments and NPK fertilizer applications [3].

Organic fertilizers encompass a diverse range of plant-derived substances, spanning from fresh or dried plant material to animal manures, litter, and agricultural by-products. They serve as exceptional soil amendments, offering a nutrient balance while enriching the soil with valuable organic matter. The application of manure to soil significantly enhances its physical and chemical properties, leading to improved maize grain yields. However, organic fertilizers generally contain lower nutrient concentrations, requiring substantial amounts for application, which can become cost-ineffective when transporting over long distances. Hence, utilizing locally accessible sources aligns perfectly with production strategies, ensuring practical and consistent use [89].

5. Conclusions

In the pot experiment, both mineral NPK and organic fertilization in variants C, D, and F demonstrated the most favorable impact on plant nutritional status and chlorophyll fluorescence measurements. The intercellular CO_2 concentration (CI) registered its highest levels in the control and post-NPK mineral fertilization. Net photo-synthesis intensity (PN) peaked following variant D fertilization, contrasting with its lowest point after NPK mineral fertilization. NPK mineral fertilization notably influenced plant height, cob length, and various yield components, including the number of grains per cob and MTZ. Variants D and F also showed a high number of grains per cob, while variant D positively affected thousand seed mass. Additionally, the highest straw dry weight and grain weight per plant were observed after NPK mineral fertilization and variant D application. The protein content in grains significantly increased following mineral or organic fertilization compared to the control. However, the results suggest that the use of organic fertilizers for corn cultivation yielded lesser effects compared to mineral NPK fertilization. This indicates that organic fertilizers alone might not entirely replace chemical counterparts. Variants E, G, and H showed a reduced performance, suggesting they might not meet the nitrogen requirements during corn's rapid growth phase. Future experiments could explore the effectiveness of individual organic fertilizers combined with mineral nitrogen fertilization alongside soil chemical analysis post-experimentation for comprehensive insights.

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