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ORIGINAL RESEARCH PAPER

Nitrogen dynamic and precise management to predict corn yield in tropical upland acid soils

A. Kasno[1], A.A. Rivaie[1], C. Tafakresnanto[1], E. Pratiwi[1], E. Karmawati[1], A. F. Siregar[2], M. Hatta[1,*], , M.T. Sutriadi[1]

[1] *National Research and Innovation Agency, Cibinong Science Center, Jl. Raya Jakarta-Bogor, Cibinong, Bogor 16915, West Java, Indonesia*

[2] *Indonesian Soil and Fertilizer Standardization Institute, Jl Tentara Pelajar, Bogor, 16114, West Java, Indonesia*

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ABSTRACT

BACKGROUND AND OBJECTIVES: To meet the needs of the global population (9.7 billion people) until 2050, a 45 percent increase in corn production is required. Efforts to enhance corn production may be informed, among others, by precise nitrogen management. The objective of this study is to investigate nitrogen dynamics and accurate nitrogen nutrient management in corn farming through the utilization of a leaf chlorophyll meter and nitrogen response assessments in order to forecast corn yield in tropical upland acid soils.

METHODS: The current study was conducted in an Ultisol and verified in an Oxisol. The trial was arranged in a randomized completely block design with eight treatments: 0, 45, 90, 135, 180, 225, 270, and 315 kilograms of nitrogen per hectare, repeated three times. The chlorophyll content of corn leaves was measured at 45 and 60 days after planting, using a chlorophyll meter. An analysis was conducted on the vegetative growth and yield, along with the nitrogen content in the soil, leaf, and grains.

FINDINGS: The study found that the application of nitrogen fertilizer at the rate of 180 kilograms per hectare can alter nitrate concentrations in soil and significantly increase nitrogen uptake, growth, and corn yield. The nitrogen fertilizer application reached its peak at 274.5 kilograms per hectare, resulting in chlorophyll meter readings of 52.8 and a corn yield of 8.58 tons per hectare. The corn yield at the rate of maximum nitrogen fertilizer (8.58 tons per hectare) was not significantly different from that at the rate of 180 kilogrammes nitrogen per hectare (8.54 tons per hectare). A robust relationship was observed between corn yields and chlorophyll meter values, exhibiting a correlation coefficient 0.92.

CONCLUSION: The study revealed that applying nitrogen fertilizer at the medium rate of 180 kilograms per hectare can increase in nitrogen uptake, growth, and corn yield on tropical upland acid soils. The corn yield did not show a notable variance between the nitrogen fertilization rate of 180 kilograms per hectare and the highest rate of 274.5 kilograms per hectare. In terms of sustainable agriculture management, the medium rate of 180 kilograms of nitrogen is recommended for maximizing crop yield on the upland acid soils and minimizing potential environmental impacts associated with the excessive use of fertilizers. A significant relationship exists between leaf chlorophyll meter measurements and corn yield, indicating that the chlorophyll meter can be utilized as a dependable instrument in the research area for establishing the most effective fertilizer levels.

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*Corresponding Author:
Email: *muha317@brin.go.id*
Phone: ***
ORCID: 0000-0003-4857-3599

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INTRODUCTION

Corn is cultivated worldwide at a yearly production rate of 1.2 billion tons, marking a 45 percent (%) surge in grain yield to meet the needs of an anticipated population growth of 9.7 billion individuals by the year 2050 (Hubert *et al.*, 2010). In Indonesia, corn is the second-most important food crop after rice. The corn cultivation area is approximately 5.73 million hectares, with a productivity rate of 5.24 tons per hectare (t/ha) (Statistic Indonesia, 2022). Corn production centers are situated on the islands of Java and Sumatra, where the land is dominated by acid upland soils that exhibit low to very low levels of fertility, particularly in terms of nitrogen (N) status (Mulyani and Sarwani, 2013). It is crucial to have balanced fertilization and nutrient status monitoring to optimize the productivity of acid-upland soils. N fertilizer plays a vital role in improving the yield of corn and other cereal crops (Selassie, 2015). Nitrogen's dynamic nature, along with its tendency to deplete soil and environmental systems, presents a unique and challenging task in managing this element effectively (Sandhu *et al.*, 2021). Accurate and responsive management of N fertilizer is critical for economic and environmental reasons in corn production. It is crucial to emphasize that elevated levels of nitrogen fertilizer application result in yields that are close to maximum, while surplus nitrogen leads to environmental pollution. However, ambiguity regarding the optimal N rate may result in profit loss. Excessive levels of fertilizer consumption can result in N surplus that may transfer to ground and surface waterways (Cantarella *et al*., 2018). Morris *et al*. (2018) reported that excessive application of nitrogen (N) fertilizer results in contamination of the air and water due to volatilization, denitrification, leaching, and runoff. Uncertainty surrounding the most effective N rate could lead to financial losses. Fertilizer prices continue to increase annually, reducing farmers' profits. Fertilization techniques are anticipated to be implemented by the findings of agronomic trials carried out in specific agro-climatic settings (Rodelo-Torrente *et al*., 2022). Several studies have shown that the nitrogen fertilizer needs of corn can be predicted using a diagnostic method that measures the light transmission properties of chlorophyll. Using a chlorophyll meter allows for real-time N management, resulting in specific and precise variable rates and crop management at a given location (Fernandes *et al.*, 2021). Implementing a chlorophyll meter has the potential to result in an increased yield, as well as enhanced N usage efficiency and N economy (Ghost *et al*., 2023). Research has been conducted to understand better the use of a leaf chlorophyll meter in managing N in corn on various soil types (Singh *et al*., 2020). To date, there is a scarcity of information regarding the utilization of the chlorophyll meter for evaluating effective nitrogen management in corn cultivation within tropical acidic upland soils in Indonesia. Conducting a fertilizer response test to establish the ideal dosage is a time-consuming and involves significant expenses. It is expected that a chlorophyll meter can be used in the study site to determine optimal fertilizer application rates based on real-time plant requirements, contributing to precision agriculture practices. The hypothesis of this study suggests that the use of N fertilizer will cause changes in nitrate concentration in the soil, leading to increased N uptake, growth, and corn yield. Furthermore, it proposes that a leaf chlorophyll meter could be utilized for precise N management of corn in tropical upland acidic soils at the study site. This study aims to determine N dynamics and precise N nutrient management in corn cultivation using a leaf chlorophyll meter and N response tests to predict corn yield on tropical upland acid soils, in Ciaruteun Udik Village, Bogor Regency, West Java Province, Indonesia, in 2021.

MATERIALS AND METHODS

Study site

The field experiment was carried out in farmers' fields situated at an altitude of approximately 321 meters: 06° 36′ 19″ south (S), 106° 40′ 23″ east (E) (Fig. 1). location experiences a tropical climate characterized by high temperatures and humidity levels, with an average yearly relative humidity ranging from 70% to 80% and an annual mean temperature of 28 degrees Celsius (°C), reaching a low of 21.2 °C and a high of 32.8 °C. The annual rainfall in the area is approximately 3,500 to 4,000 millimeters (mm). The verified site was located in Jati Agung Village, South Lampung Regency, Lampung Province, Indonesia (Sumatra Island): 105° 23′ 21″ E, 05° 14′ 02″ S (Fig. 1), at an altitude of approximately 63 meters (m). The village has a warm and humid climate with a mean annual relative humidity of 70% to 85%. The average yearly temperature is 32 °C, and

Fig. 1: Geographic location of the study area in the trial site areas, Cibungbulang, Bogor Regency, West Java Province, and Jati Agung, South Lampung Regency, Lampung Province, Indonesia

the mean annual rainfall is 2,000 - 2,500 mm.

Experimental design

The fertilization response experiment employed a fully randomized block design comprising eight treatments. The experimental conditions included eight levels: 0, 45, 90, 135, 180, 225, 270, and 315 kilogram (kg) nitrogen per hectare (N/ha). It should be noted that the recommended N fertilizer rate for hybrid corn in the research area is 221.6 kg N/ha (Tobing *et al*., 2022). The experimental procedures were replicated thrice, with urea fertilization utilized as the nitrogen source at three different intervals: 10, 25, and 40 days post planting (DAP). Urea is applied 5 cm from the plant row to a depth of 3 centimeters (cm), then covered with a layer of topsoil. Phosphorus (P) and potassium (K) fertilizers were applied as basic fertilizer at a rate of 63 kg phosphorus pentoxide per hectare (P_2O_5/ha) (10 DAP) and 60 kg potassium oxide per hectare (K_2O/ha) (50% at 10 DAP and 50% at 25 DAP). Meanwhile, the effects of N fertilizer on ammonium (NH_4^+) and nitrate (NO_3^-) concentrations in acid soil used four treatments of N fertilizer rate (0, 90, 180, and 315 kg N/ha). The plot size is 5.25 m x 5 m, with a width between plots of 30 cm and a height of 25 cm to prevent nutrient contamination. Hybrid corn seeds are sown at a distance of 25 cm x 75 cm, with one seed placed in each planting hole. Prior to sowing, the corn seeds undergo treatment with pesticides that consist of 4% mefenoxam and 64% mancozeb in order to protect against downy mildew. The validation study conducted at the Jati Agung site included experiments on nine farmers' fields, with the collaboration of farmers and researchers. The

Fig. 2: Land preparation and performance of corn plants on experimental site

Fig. 3: Leaf chlorophyll measurements with SPAD

farmers employed varying rates of N fertilizer, namely 308, 315, and 335 kilograms per hectare (kg/ha). During the verification process in Jati Agung, basal applications are exclusively implemented, involving the incorporation of P fertilizer (Ben Guerir phosphate rock, Morocco) at a rate of 1 t/ha, dolomite at 1 t/ha, and manure at a rate of 2 t/ha during soil tillage. Land preparation and performance of corn plants are presented in Fig. 2.

Chlorophyll meter analysis

The chlorophyll content of corn leaves was analyzed at 45 and 60 DAP (Fig. 3). The levels of chlorophyll in the foliage were measured in 10 individual plants within each designated plot that had been specifically chosen and identified. The chlorophyll measuring tool was Minolta Soil Plant Analysis Development (SPAD) 502 (Ciganda *et al*., 2009) at 45 DAP (V12) and 60 DAP (VT at tasselling) in ten samples per plot (Ortez and Lindsey, 2022). Each leaf sample was measured three times.

Plant and soil analysis

Samples consist of leaves and upper stems of plants, taken when most of the plant population is prepared for harvesting. Ten plant sub-samples were trimmed 3 cm above the ground level and rinsed with fresh water to eliminate dust and debris. The ten

Table 1: Characteristics of soil From Cibungbulan, Bogor Regency, West Java Province, and Jati Agung, South Lampung Regency, Lampung Province, Indonesia

Soil characteristics	Cibungbulang (Values)	Jati Agung (Values)
pH soil: water (1:5)	5.2	4.4
pH soil: potassium chloride (1:5)	4.7	4.0
Carbon (C) organic (%)	1.23	1.04
Nitrogen (N) total (Kjeldahl) (%)	0.11	0.10
Exchangeable cations:		
Calcium (Ca) centimoles per kilogram (cmol(+)/kg	11.13	1.23
Magnesium (Mg) (cmol(+)/kg)	1.84	0.26
Potassium (K) (cmol(+)/kg)	0.20	0.14
Cation exchange capacity (CEC) (cmol(+)/kg)	16.88	5.81
Base saturation (%)	79	30
Soil texture:		
Sand (%)	6	25
Silt (%)	43	33
Clay (%)	51	42

corn stalks were combined, cut into pieces taken 1 kg sample representing the treatment, and put into one paper bag. Plant samples were dried in an oven at 70℃ for two days. Following this, the plant samples undergo grinding until reaching a consistent texture, thereby becoming prepared for analysis in the controlled environment of the laboratory. Prior to the treatment, soil samples were randomly collected to accurately represent the designated land area for the experiment. The composite soil sample consists of 5 subsamples taken in a distributed manner to a depth of 0-20 cm. The five sub-samples were aggregated and blended, after which 1 kg was extracted. The soil samples underwent air-drying, grinding, and sieving with a 2 mm diameter sieve, before being dispatched to the laboratory for analysis. Analysis of total plant N nutrients was conducted using the Kjeldahl method using wet ashing with sulfuric acid (H_2SO_4). Soil sampling was carried out at the same time as plant sampling from the same experimental plot. Soil samples were extracted from a depth of 0–20 cm, after the elimination of plant residues, gravel, and stones. These samples were then air-dried, pulverized using a mortar, and sifted through a 2 mm sieve. Subsequently, the soil samples were forwarded to the Soil Research Institute laboratory for examination of NH_4^+ (Blakemore *et al*., 1987) and NO_3^- (Keeney and Nelson, 1982). The soil potential of hydrogen (pH) was measured using a soil-to-water (w/w) ratio of 1:5. Soil suspensions were blended and stored at a controlled temperature of 20±2 ℃ overnight to obtain accurate measurements. pH values were subsequently assessed using a pH meter, following the method described in Blakemore *et al*. (1987). Samples were heating in a Leco furnace to ascertain the percentage of carbon, which represents the soil organic matter content. A high-quality oxygen stream was introduced to convert organic matter to carbon dioxide (CO_2) during this process. The infrared detector was utilized to measure the quantity of CO_2 present, which was then used to compute the total organic carbon content. Exchangeable cations and cation-exchange capacity (CEC) were determined by leaching with ammonium acetate at pH 7. The amounts of potassium (K), calcium (Ca), magnesium (Mg), and sodium (Na) in the leachates were determined using atomic absorption spectrometry (AAS) (Blakemore *et al*., 1987) (Table 1).

The dried leaf samples were ground using a portable grinder. The resulting powder was then digested in 1 liter (L) of concentrated H_2SO_4 with a Kjeldahl digestion blend containing 1 gram (g) of selenium powder and 100 g of potassium sulphate (K_2SO_4) (95-97%). N content in the digest was determined using a technical auto-analyzer (Blakemore *et al*., 1987). The N uptake of corn was determined by the multiplication of the N levels in individual plant parts with their respective dry matter weight. The total nitrogen uptake of corn was equivalent to the combined nitrogen uptake of all plant components.

Data analysis

Data analysis was conducted on vegetative growth and corn yield, as well as N concentration in the soil, corn leaf, and grain. The analysis of variance (ANOVA) for a randomized complete block design

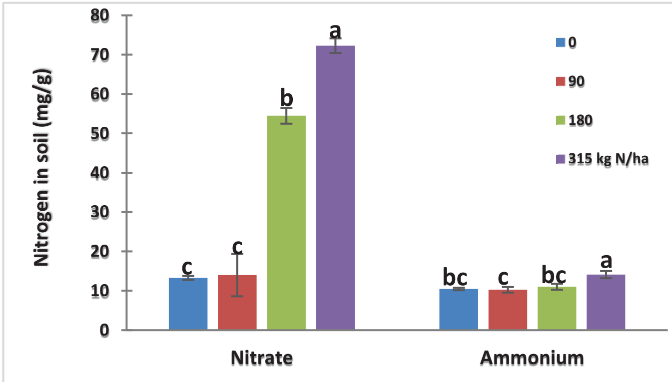


Fig. 4: Effects of N fertilizer on Ammonium and Nitrate concentrations in acid soil of Cibungbulang, Bogor Regency. Bars with identical letters at the top are not different according to the DMRT at $P < 0.05$

was carried out using a statistical package for the social sciences (SPSS) Statistics v27 (2020). Upon observing significant treatment effects as determined by ANOVA, Duncan's Multiple Range Test (DMRT) was utilized at a significance level of $P < 0.05$, unless stated otherwise (Steel and Torrie, 1997).

RESULTS AND DISCUSSION

Soil characteristics in both sites

The examination of the soil profile indicated that the soil type found in Cibungbulang is Ultisols, originating from lava flow and andesite as the soil parent material (Widiatmaka *et al.*, 2015). The soil analysis results indicate that the soil pH, hydrogen oxide (H_2O) is acidic (5.2), and the texture at a depth of 0-20 cm is clay (6% sand, 43% silt, and 51% clay). The soil sample analysed in this study has a low organic carbon content of 1.23% and a low N-total of 0.11%. The study area's soil is marked by a predominant Ca cation, making up 84% of the total cation exchange capacity (CEC) with a value of 16.88 (cmol$^{(+)}$/kg) and 79% base saturation (Blakemore *et al.*, 1987). Within the region of Jati Agung, the soil type is identified as Oxisols, characterized by a notably low pH level of 4.4 in water. The predominant cation within this soil is Calcium, making up 75% of the total CEC value of 5.81 cmol$^{(+)}$/kg, with a base saturation of 30%. The organic carbon content is low at 1.04%, and the total N content is low at 0.10%. The texture at a 0-20 cm depth is clay, consisting of 25% sand, 33% silt, and 42% clay (Table 1).

Effects of N fertilizer on nitrate-nitrogen (NO_3^--N) and ammonium-nitrogen (NH_4^+-N) concentrations

The measurement at 30 DAP revealed that applying N fertilizer significantly influenced the concentrations of NO_3^--N and NH_4^+-N in the 0-20 cm soil depth. The soil NO_3^--N concentration experienced a significant rise with the addition of 180 and 315 kg N/ha. This significant effect of the medium nitrogen rate (180 kg N/ha) was most probably because of the low level of the total nitrogen content in the soil (0.11%) (Pasley *et al.*, 2019). The soil NH4+-N concentration did not show an increase when the medium N rate (180 kg N/ha) was applied. The concentration of NH_4^+-N only significantly increased at the high N rate (315 kg N/ha) (Fig. 4). In the soil solution, NH_4^+-N and NO_3^--N are the most important forms of inorganic N due to their ready availability for plant absorption (Cassman *et al.*, 2002). Adding 315 kg N/ha resulted in an approximately 18.5% increase in soil NO_3^--N concentrations. The concentration of NH_4^+-N significantly increased only when a high N rate, even though both soil sites in this study had low N-total (0.11% and 0.10%) and a low organic carbon content (1.23% and 1.04%) (Table 1). The shapes exhibit great mobility, are readily soluble, and have the ability to change the structure of the plants that they are absorbed by. Losses can occur due to various processes including leaching, nitrification, denitrification, evaporation, and surface or lateral flow (Chen *et al.*, 2008). Excessive nitrogen and water inputs can lead to significant nitrate-N (NO_3^--N) leaching, posing a threat to the sustainability

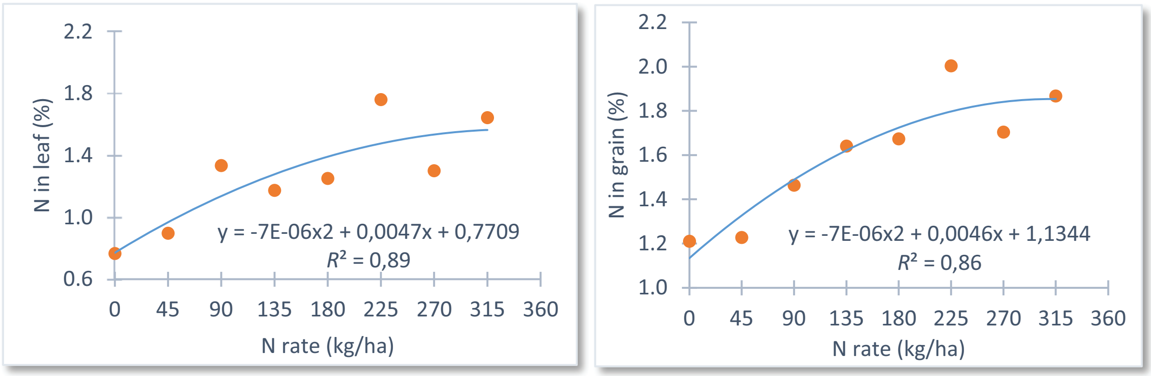


Fig. 5: Relationship between N fertilization and N concentration in corn leaves and grains in Cibungbulang, Bogor Regency, West Java, Indonesia, dry season 2021

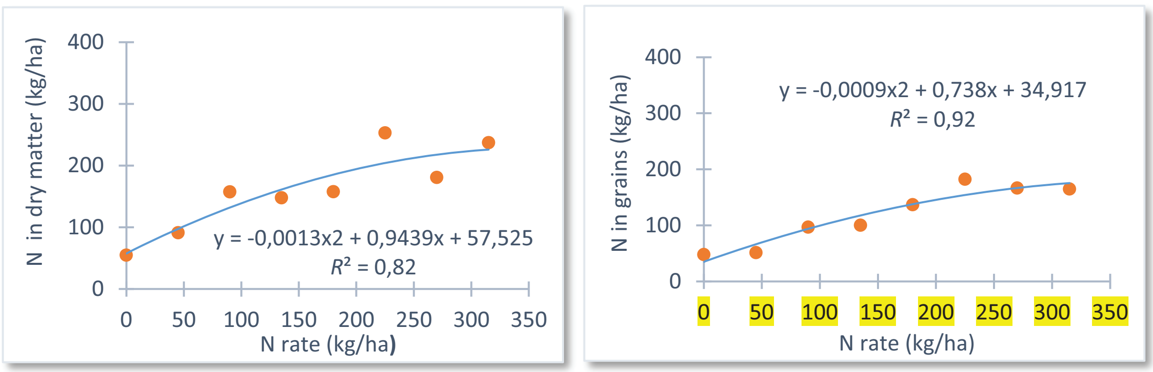


Fig. 6: Relationships between N fertilizer and N uptake in dry matter and grains

of traditional agriculture in the North China Plain (NCP) (Wang *et al*., 2018). Zhou and Butterbach-Bahl (2014) reported that approximately 15% of N fertilizer in corn plants is lost through leaching in the form of NO_3^--N. Furthermore, research findings have shown that cereal crops display limited effectiveness in uptaking N fertilizer, as they absorb less than half of the total N provided. For example, in the case of corn plants, the percentage of N nutrients lost through evaporation varied between 11% and 48%, denitrification rates ranged from 0.8% to 1.2%, and N_2O emissions were recorded at 0.9% to 1.7% relative to the amount of N-Urea applied to the plants (Cai *et al*., 2002). The addition of 90 kg N/ha did not increase NO_3^--N and NH_4^+-N levels in the soil, it is important to note that compared to the control group receiving 0 kg N/ha, the addition of 90 kg N/ha led to significant improvements in various aspects, such as N uptake, corn growth, and yield.

Effects of N fertilization on N uptake by corn plant

The empirical findings indicate the presence of noteworthy quadratic associations between the N levels in both the leaves and grains of corn, and the rates of N fertilizer application (R^2 = 0.89, P = 0.040; R^2 = 0.86, P = 0.008, respectively) (Fig. 5). This indicates that the application of N fertilizer influences the nitrogen levels in the leaves.

The application of N fertilizer also significantly affected the N uptake in corn grains (Fig. 5). The regression analysis unveiled substantial quadratic connections between N assimilation in corn dry matter and grain and N fertilizer rate (R^2 = 0.82, P = 0.013; R^2 = 0.92, P = 0.002, respectively) (Fig. 6). This indicates that the application of N fertilizer led to a rise in N absorption in both dry matter and corn grain following a quadratic trend.

Effects N fertilization on leaf chlorophyll values

The addition of N fertilizer significantly affected

Table 2: The influence of N fertilizer addition on corn leaf chlorophyll meter values in an acid soil (Ultisols) of Cibungbulang, Bogor Regency, West Java, Indonesia

N rate (kg/ha)	Chlorophyll meter values	
	45 DAP	60 DAP*
0	40.58c	37.55d
45	42.71c	41.71c
90	48.79b	51.72b
135	49.28b	52.21b
180	54.68a	56.48a
225	53.84a	56.78a
270	52.46ab	57.00a
315	53.70a	56.92a

* = Numbers with identical letters within the same column are not different according to the DMRT at $P < 0.05$.

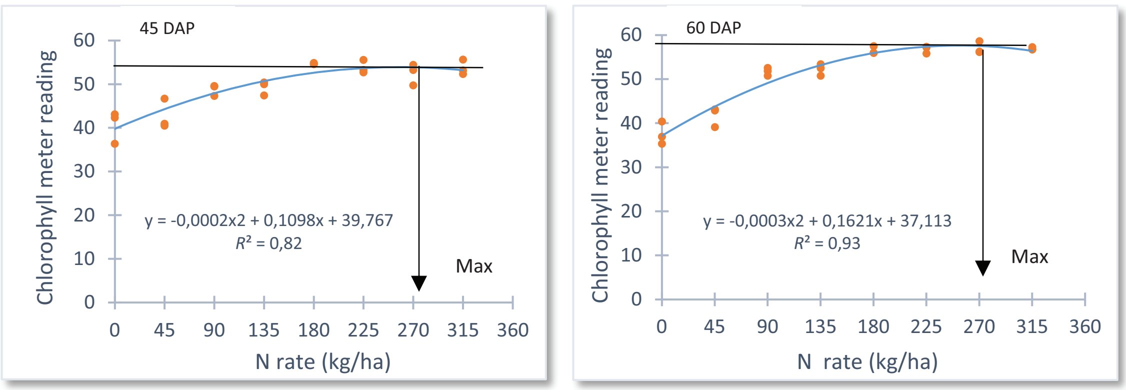
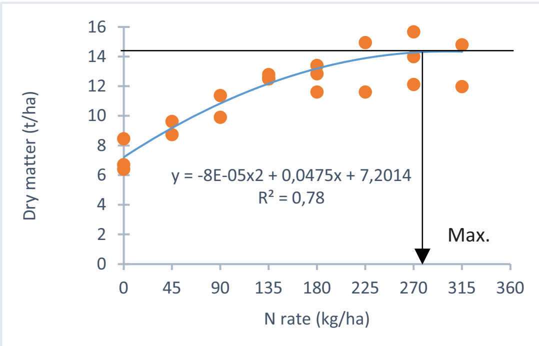


Fig. 7: Relationships between N fertilizer with corn leaf chlorophyll at 45 DAP and 60 DAP

the chlorophyll meter values of the leaves. Increasing the N fertilizer rate resulted in higher chlorophyll readings in corn leaves compared to the control group (Table 2). Nevertheless, the application of nitrogen fertilizer exceeding 180 kg N/ha did not result in a notable enhancement in chlorophyll levels, instead reaching a point of saturation. Remarkable quadratic correlations were noted between leaf chlorophyll levels and nitrogen fertilizer application rate (Fig. 7). The coefficient of determination for the link between applied N rates and leaf chlorophyll readings measured at 60 DAP ($R^2 = 0.93$, $P < 0.001$) was higher than that measured at 45 DAP ($R^2 = 0.82$, $P < 0.001$). When the values of the leaf chlorophyll meter were measured at 60 DAP and regressed with the leaf N contents, a significant quadratic relationship was observed ($R^2 = 0.93$, $P < 0.001$). The results indicate that assessing the sufficiency of N nutrient in corn plants with a chlorophyll meter is more effective when conducted at the tasselling stage (60 DAP) than during kernel primordium initiation (45 DAP).

At 45 DAP, the corn leaf chlorophyll measurement indicated a maximum N fertilizer rate of 274.5 kg N/ha, with corresponding chlorophyll meter readings of 52.8 (Figs. 7) and a corn yield of 8.58 t/ha (Fig. 8). At 60 DAP, the measurement of chlorophyll in the corn leaves was indicated a maximum N fertilizer rate of 270.2 kg N/ha, corresponding to chlorophyll meter readings of 59.0 (Fig. 7) and a corn yield of 8.50 t/ha (Fig. 8).

Table 3 shows a strong correlation between soil NO_3^--N concentration and leaf N, corn leaf chlorophyll, N uptake, and corn growth and yield ($r = 0.82$**; $r = 0.75$**; $r = 0.89$**; $r = 0.71$**; and $r = 0.75$**). The findings indicate that the introduction of N fertilizer led to alterations in soil NO_3^--N levels and their movement. Subsequent to these soil modifications, a notable rise in leaf N levels, chlorophyll content, N absorption, corn development, and crop yield was observed. The results indicate that the N fertilizer rate derived from chlorophyll meter readings should be 274.5 kg N/ha to achieve maximum yield. The rate



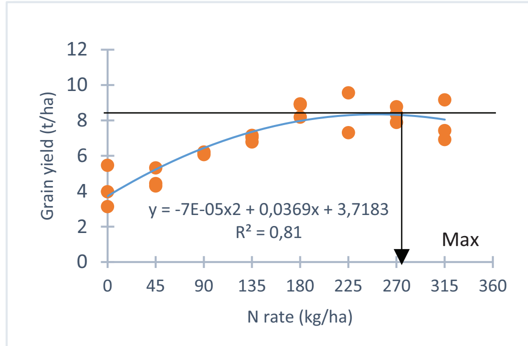


Fig. 8: Relationships between N fertilizer with dry matter weight and grain yield

Table 3: Correlation matrix for NH_4^+-N and NO_3^--N in soil, chlorophyll meter readings, N uptake in corn dry matter and grains, dry matter, and yield for all N rates in acid soil of Cibungbulang, Bogor, West Java, Indonesia

Parameters	NH_4^+-N in soil	NO_3^--N in soil	Leaf N	N uptake in DM	N uptake in grains	CMR	Corn DM	Corn yield
NH_4^+-N in soil	1							
NO_3^--N in soil	0.79**	1						
Leaf N	0.79**	0.82**	1					
N uptake in DM	0.65*	0.89**	0.90**	1				
N uptake in grains	0.54	0.63*	0.77**	0.56**	1			
CMR	0.49	0.75**	0.81**	0.58**	0.80**	1		
Corn DM	0.52	0.71**	0.73**	0.57*	0.82**	0.80**	1	
Corn yield	0.40	0.75**	0.64*	0.52*	0.83**	0.92**	0.84**	1

* = Correlation coefficient is significant at $P < 0.05$; ** = Correlation coefficient is significant at $P < 0.01$; CMR = Chlorophyll meter readings; DM = Dry matter

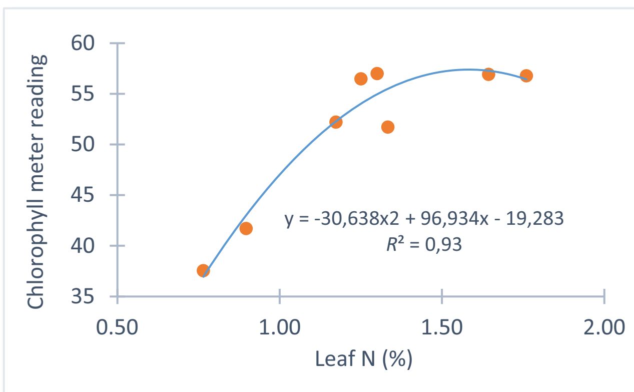


Fig. 9: Relationships between leaf N concentrations with corn leaf chlorophyll

derived from the fertilization response test should be 263.7 kg N/ha (Figs. 8 and 9).

Corn growth and yield responses to N fertilization

Elevated levels of nitrogen fertilizer typically led to greater plant height, cob diameter, dry matter weight, and grain yield compared to the untreated group (Table 4). Application of N fertilizer at levels higher than 135 kg N/ha did not result in a noticeable enhancement in plant height or cob diameter. The application of N fertilization at a rate of 90 kg N/ha resulted in a higher yield compared to rates of 0 and

Table 4: Influence of N fertilization on plant height, cob diameter, weight of dry matter and yield in a tropical acid upland soil of Cibungbulang District, Bogor Regency, Indonesia

N rate (kg/ha)	Plan height (cm)	Cob diameter (mm)	Dry matter (t/ha)	Yield* (t/ha)
0	222.7c	48.0b	7.19d	4.20c
45	237.4b	51.4b	10.19cd	4.69c
90	250.6a	57.2a	11.82bc	7.01b
135	253.5a	56.3a	12.61abc	7.00b
180	257.9a	59.9a	12.63abc	8.64a
225	254.5a	61.4a	15.77a	8.58a
270	262.0a	61.3a	13.93ab	8.34ab
315	251.5a	59.5a	14.44ab	7.84ab

* = Numbers with identical letters within the same column are not different according to the DMRT at $P < 0.05$

45 kg N/ha. The application of 90 kg N/ha fertilizer did not lead to a notable variation in corn grain production when compared to the application of 135 kg N/ha. However, the utilization of 180 kg N/ha significantly boosted the corn yield in contrast to the 135 kg N/ha application rate. The significant increase in corn yield following the application of the medium N rate (180 kg N/ha) was most probably because of the low level of the total N content in the soil (Pasley *et al.,* 2019). The regression analysis revealed significant quadratic relationships between the dry matter and yield with N fertilizer rate (R^2 = 0.78, $P < 0.001$; R^2 = 0.81, $P < 0.001$, respectively) (Fig. 8). These results indicate a strong response of the yield (t/ha) to the application of N fertilizer.

The excessive application of nitrogen fertilizer has been proven to have the potential to lower corn yields and disrupt the balance of nutrients in the soil, ultimately leading to decreased crop productivity (Moser *et al.,* 2006). In order to avoid the need for a higher rate of nitrogen fertilizer, a decrease in the amount of nitrogen available to plants requires a more efficient method of delivering fertilizer (Quinn *et al.*, 2023). Recent research has demonstrated that corn plants reach their peak yields when grown nutrient-rich soils (Davies *et al.*, 2020). Nitrogen is the primary limiting nutrient for corn production. Insufficient levels of this factor can cause a decline in harvests by impeding the development of plants (Kablan *et al.*, 2017). The soil in the experimental site has a low total N concentration of 0.11% (Table 1), which could be the reason why the addition of médium N fertilizer significantly enhanced the growth and yield of corn. Corn production exhibited a quadratic pattern in response to the increasing N rate application. In this study, the maximum recommended N fertilizer rate for acid soil in Cibungbulang District, Bogor Regency was 263.7 kg N/ha (eq. 573 kg urea per hectare (urea/ha), which resulted in a yield of 8.58 t/ha. The optimum rate, which yielded 90% of the maximum yield, was 237 kg N/ha (eq. 515.2 kg urea/ha). It is worth mentioning that a study conducted in Pakistan demonstrated that the recommended N fertilizer rate for corn plants was initially set at 200 kg N/ha, but was later found to be inadequate for specific soil conditions, leading to an adjustment to 300 kg N/ha (equivalent to 650 kg urea/ha) (Khaliq *et al.*, 2009). They found that adding N fertilizer above this rate yielded a lower yield. Appropriate N management can increase corn yields and reduce the possible loss of N due to leaching to the layers beneath the root zone. Singh *et al.* (2020) also supported this finding.

The results of the verification site

The findings from tests performed by various farmers at the verification sites (Oxisols) in Jati Agung, South Lampung Regency, Lampung Province have been documented in Table 5.

The results of the Cibungbulang site (Ultisols) revealed that the maximum N fertilizer rate for corn derived from the fertilization response test was 263.7 kg N/ha. Rates of N used by farmers at the Jati Agung site (Oxisols) ranged from 308 to 335 kg N/ha, which appears to be quite higher than the maximum N rate required in the Cibungbulang location. The values of chlorophyll meter readings observed at the verification site on day 45 after planting (DAP) fell within the range of 54.2 to 59.5 (Table 5). At the Cibungbulang site, the maximum N fertilizer rate observed was 274.5 kg N/ha, linked to a chlorophyll meter value 52.8 and a corn yield of 8.58 t/ha. These results imply that adjustments are necessary for the N fertilizer rates utilized in the soils at Jati Agung, with consideration given to the chlorophyll meter readings

Table 5: Influence of N fertilizer on the values of corn leaf chlorophyll meter and yields in a tropical acid upland soil (Oxisols) at Jati Agung District, South Lampung Regency, Indonesia

Farmer location (Coordinates)	N rate (kg N/ha)	Chlorophyll meter values (45 DAP)	Yield (t/ha)
1. - 05° 14' 03" S; 105° 23' 35" E	315	54.2	7,88
2. - 05° 14' 16" S; 105° 23 '42" E	335	54.2	6,20
3. - 05° 14' 07" S; 105° 23' 27" E	315	55.1	6,40
4. - 05° 14' 03" S; 105° 23' 35" E	308	55.2	6,30
5. - 05° 14' 03" S; 105° 23' 35" E	315	56.6	7,00
6. - 05° 14' 12" S; 105° 23' 42" E	335	56.7	5,83
7. - 05° 14' 11" S; 105° 23' 41" E	335	57.2	7,42
8. - 05° 14' 04" S; 105° 23' 31" E	315	57.7	6,44
9. - 05° 13' 57" S; 105° 23' 22" E	335	59.5	5,77

SL = South latitude; EL = East longitude; DAP = Days after planting

associated with the highest yield, specifically 315 kg N/ha, in relation to a chlorophyll meter value of 54.2 and a yield of 7.88 t/ha (Table 5). The results in this verification site confirmed that this procedure can be applied for corn N management and grain yield estimation in the Oxisols of South Lampung as well.

Precise nitrogen management

Recent findings by Kaur *et al.* (2024) indicate that elevated levels of N fertilizer application have the potential to enhance the production of corn. The importance of tailoring nitrogen management practices to the specific characteristics of the soil for corn cultivation on a yearly basis is highlighted by factors such as the presence of inorganic nitrogen in the soil, precipitation patterns, and soil pH, as outlined in the study conducted by Hao *et al.* (2020). Managing N for corn in the southeastern United States, for instance, requires tailored N management due to the varying yield fluctuations resulting from numerous factors specific to each location (Raza and Farmaha, 2022). Corn plants reach their fastest growth phase and accumulate considerable organic matter during the V12 - VT phase (45-60 DAP), demanding a substantial supply of N to support their growth (Ortez and Lindsey, 2022). It is crucial to closely monitor the sufficiency of nitrogen during the V12 – VT stage to achieve the best possible outcomes. In this study, the measurements of leaf chlorophyll were conducted at 45 DAP (V12, five days after the third urea application) and 60 DAP (VT, during the tasselling). In line with these results, there is a strong direct association between the normalized values of chlorophyll meter and normalized corn production in a field experiment of cropping systems conducted on Hord silt loam soil (Varvel *et al.*, 2007). Through this study, a quadratic model was developed to determine the ideal rates of side-dress nitrogen application for maximizing corn production. This model has the capacity to provide nitrogen recommendations tailored to individual sites (Varvel *et al.*, 2007). Employing a SPAD chlorophyll meter enables real-time monitoring of paddy N levels and the estimation of grain yield. This tool is considered a trustworthy asset in comprehending and addressing spatial fluctuations within double-cropping rice fields utilizing precision agriculture methods (Gholizadeh *et al.*, 2017). The study found a strong and precise correlation between soil NO_3^--N concentration and leaf N, corn leaf chlorophyll, N uptake, and corn growth and yield (Table 3). This suggests a change in NO_3^--N concentrations in the soil, followed by a significant increase in leaf N concentrations, chlorophyll values, N uptake, corn growth, and yield. The significant correlations found between corn yield and chlorophyll meter values provide strong evidence for the reliable use of leaf chlorophyll meters in precision agriculture for corn N management in the Ultisol of the study site. Soil N availability is likely the most influential factor in determining the leaf greenness of plants in the field. The N nutrient in the enzymes is responsible for chlorophyll synthesis (Wen *et al.*, 2019). In the current era, the focus lies on optimizing nitrogen usage efficiency to safeguard financial resources while upholding agricultural productivity and environmental security worldwide. This involves tackling issues such as greenhouse gas emissions, ammonium volatilization, and nitrate leaching (Anas *et al.*, 2020). This statement highlights that the level of chlorophyll can be a dependable indicator of the N fertility of a soil type in each location.

CONCLUSION

The study revealed that applying N fertilizer at the medium rate of 180 kg N/ha an increase in N uptake, growth, and corn yield on tropical upland acid soils (Ultisols and Oxisols). The considerable effects of the medium N rate can be largely attributed to the relatively low total N content within the soil. This implies that the medium N rate is particularly effective in soil types commonly encountered in tropical regions, which are frequently characterized by inadequate levels of nitrogen availability. The limited natural N supply making it challenging for crops to obtain sufficient N for optimal growth and development. Through the utilization of a moderate dosage of nitrogen fertilizer, farmers are able to effectively address this lack of nutrients and stimulate the healthy development of plants. The increased N uptake and corn yield observed in the study can be attributed to the improved availability of N in the soil, which allows plants to access essential nutrients more readily. There was not a significant difference in corn yield between the rate of N fertilization at 180 g N/ha and the maximum rate of 274.5 kg N/ha. In terms of sustainable agriculture management, the medium rate of 180 kg N/ha is recommended for maximizing crop yield on the upland acid soils and minimizing potential environmental impacts associated with excessive use of fertilizers. This new recommended rate will greatly reduce the current recommended rate of N fertilizer on the upland acid soils (180 vs 221.6 kg N/ha). This is a crucial finding, as it suggests that excessive use of fertilizers may not necessarily lead to higher crop yields. The excessive utilization of fertilizer may cause harmful environmental outcomes, such as soil pollution and water contamination. Hence, it is recommended to adopt a more sustainable approach to nitrogen fertilizer management on acidic upland soils. Specifically, the medium rate of 180 kg N/ha is suggested as the optimal rate for maximizing crop yield while minimizing environmental impacts. This new recommended rate is significantly lower than the current recommended rate of 221.6 kg N/ha, which means that farmers can reduce their N fertilizer use by about 20%. The adjustment in recommendation is noteworthy as it underscores the importance of integrating agricultural productivity with environmental sustainability. By adopting a more moderate approach to N fertilization, farmers can not only reduce their environmental footprint but also reduce their costs and improve soil health. Furthermore, this approach has the potential to play a role in lessening the impact of climate change by cutting down on greenhouse gas emissions connected to the production and application of fertilizers. The rate of N fertilizer to attain optimal yields as determined by the chlorophyll meter reading closely matches the amount determined by the nitrogen fertilization response test. There is a strong correlation between leaf chlorophyll meter readings and corn yield. Additionally, the study revealed that the use of a leaf chlorophyll meter for assessing N status and forecasting corn yield is more accurate during the tasselling phase as opposed to the kernel primordium initiation phase. These suggest that the chlorophyll meter can serve as a reliable tool in the study site in determining optimal N fertilizer application rates based on real-time plant requirements, contributing to precision agriculture practices. The optimization of fertilizer application rates is of great importance in precision farming, as it allows farmers to enhance their cultivation methods. One of the key advantages of using the chlorophyll meter is that it can provide a more accurate assessment of N status and yield potential compared to traditional methods, such as the N fertilization response test. This is because the chlorophyll meter's capability to promptly assess nitrogen levels enables farmers to make timely adjustments to their fertilizer application rates. The study also found that the chlorophyll meter is more effective during the tasselling phase than during the kernel primordium initiation phase. The implication is that farmers need to employ the meter at the critical growth stages marked by elevated nitrogen uptake, particularly during grain filling and silking. This approach can verify that plants acquire the required nitrogen for ideal growth and yield. Further studies are necessary to increase corn productivity through precise N management using leaf chlorophyll meters in various types of tropical upland soils. For example, research should be conducted to investigate the impact of different types of manure (e.g., chicken, cow, or pig) addition as a N source on corn yield and N management. The optimal application rates of manure and its interaction with other nutrients (e.g., P, K) should be studied. Developing integrated nutrient management strategies that blend diverse nitrogen sources like synthetic fertilizers, manure, and cover crops with sound management practices is essential for maximizing corn productivity in tropical upland soils. Through the pursuit of additional research to fill these knowledge gaps, farmers can elevate their understanding of N management in tropical upland soils by utilizing leaf chlorophyll meters. This will enable them to devise more robust strategies to enhance sustainable corn productivity.

AUTHOR CONTRIBUTIONS

A. Kasno led the review design, structured the outline, and performed data analysis. A.A. Rivaie structured the outline, offered critical input, and provided insights. C. Tafakresnanto structured the outline and provided specialized expertise by reviewing the data meticulously. E. Pratiwi performed field and laboratory work, data analysis, and provided insights. E. Karmawati performed the data analysis, drafted and revised the manuscript, and provided insights. A.F. Siregar structured the outline, performed field and laboratory work, and graphical abstract. M. Hatta acted as the corresponding author, drafted and revised the manuscript, provided specialized expertise by reviewing the data meticulously, and offered critical input. M.T. Sutriadi performed the data análisis, graphical abstract, and expertise in reviewing the data meticulously.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

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ABBREVIATIONS

%	Percent
°C	Degrees Celsius
±	Plus minus
AAS	Atomic absorption spectrophotometer
ANOVA	Analysis of variance
C	Carbon
Ca	Calcium
CEC	Cation exchange capacity
cm	Centimeter
CMR	Chlorophyll meter readings
cmol(+)/kg	Centimoles per kilogram
CO_2	Carbon dioxide
DAP	Days after planting
DM	Dry matter
DMRT	Duncan Multiple Range Test
E	East
g	Gram
H_2O	Hydrogen oxide
H_2SO_4	Sulfuric acid

K	Potassium
kg	Kilogram
K_2O	Potassium oxide
K_2O/ha	Potassium oxide per hectare
K_2SO_4	Potassium sulfate
Kg/ha	Kilograms per hectare
L	Liter
m	Meter
Mg	Magnesium
mg/kg	Miligram per kilogram
mm	Millimeter
N	Nitrogen
Na	Natrium
NH_4^+	Ammonium
NH_4^+-N	Ammonium-Nitrogen
NO_3^-	Nitrate
NO_3^--N	Nitrate-Nitrogen
N_2O	Nitrous oxide
N/ha	Nitrogen per hectare
P	Phosphorus
pH	Potential of Hydrogen
P_2O_5	Phosphorus pentoxide
P_2O_5/ha	Phosphorus pentoxide per hectare
S	South
SPAD	Soil Plant Analysis Development
t/ha	Tons per hectare
Urea/ha	Urea per hectare
VT	Vegetative growth in which the last branch of the tassel is visible
V12	Vegetative growth, the plant equipped with 10 leaf collars has a rapidly growing stalk
w/w	Weight-to-weight

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AUTHOR (S) BIOSKETCHES

Kasno, A., M.Sc., Researcher, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor, km. 46, Cibinong, Bogor 16915, West Java, Indonesia.

- Email: *kasn002@brin.go.id*
- ORCID: 0000-0003-0289-5314
- Web of Science ResearcherID: KII-4842-2024
- Scopus Author ID: 57214275991
- Homepage: https://brin.go.id/orpp

Rivaie, A.A., Ph.D., Researcher, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor, km. 46, Cibinong, Bogor 16915, West Java, Indonesia.

- Email: *aari001@brin.go.id*
- ORCID: 0000-0003-4445-0372
- Web of Science ResearcherID: KII-2957-2024
- Scopus Author ID: 23568322700
- Homepage: https://brin.go.id/orpp

Tafakresnanto, C., Ph.D., Researcher, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor, km. 46, Cibinong, Bogor 16915, West Java, Indonesia.

- Email: *chen001@brin.go.id*
- ORCID: 0009-0003-6913-7670
- Web of Science ResearcherID: KPY-2969-2024
- Scopus Author ID: 57214066577
- Homepage: https://brin.go.id/orpp

AUTHOR (S) BIOSKETCHES

Pratiwi, E., Ph.D., Researcher, Indonesian Soil and Fertilizer Standardization Institute, Jl Tentara Pelajar, Bogor, 16114, West Java, Indonesia.
- Email: *etty006@brin.go.id*
- ORCID: 0000-0002-9137-4790
- Web of Science ResearcherID: GPF-5072-2022
- Scopus Author ID: 57204959313
- Homepage: https://brin.go.id/orpp

Karmawati, E., Ph.D., Researcher, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor, km. 46, Cibinong, Bogor 16915, West Java, Indonesia.
- Email: *elna001@brin.go.id*
- ORCID: 0000-0003-0070-5652
- Web of Science ResearcherID: E-5366-2013
- Scopus Author ID: 26531334600
- Homepage: https://brin.go.id/orpp

Siregar, A.F., Ph.D., Standardization Analyst, Indonesian Soil and Fertilizer Standardization Institute, Jl Tentara Pelajar No. 12, Bogor, 16114, West Java, Indonesia.
- Email: adhasiregar@pertanian.go.id
- ORCID: 0000-0002-8801-4049
- Web of Science ResearcherID: KPP-3681-2024
- Scopus Author ID: 57218377718
- Homepage: https://bsip.pertanian.go.id

Hatta, M., Ph.D., Researcher, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor, KM. 46, Cibinong, Bogor 16915, West Java, Indonesia.
- Email: *muha317@brin.go.id*
- ORCID: 0000-0003-4857-3599
- Web of Science ResearcherID: KPY-0762-2024
- Scopus Author ID: 57216193560
- Homepage: https://brin.go.id/orpp

Sutriadi, M.T., Ph.D., Researcher, National Research and Innovation Agency (BRIN), Cibinong Science Center, Jl. Raya Jakarta-Bogor, KM. 46, Cibinong, Bogor 16915, West Java, Indonesia.
- Email: *mast003@brin.go.id*
- ORCID: 0000-0002-9421-9470
- Web of Science ResearcherID: rid82803
- Scopus Author ID: 57214073103
- Homepage: https://brin.go.id/orpp

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