

# Unraveling key determinants of corn productivity: A correlation study of soil chemistry, biology, and climate in Sumedang, West Java, Indonesia

MARENDA ISHAK SONJAYA SULE\*, BETTY NATALIE FITRIATIN, SHANTOSA YUDHA SISWANTO, ANNE NURBAITY

Department of Soil Science and Land Resources, Faculty of Agriculture, Universitas Padjadjaran. Jl. Raya Bandung Sumedang KM 21, Sumedang 45363, West Java, Indonesia. Tel.: +62-228-4288890, \*email: marena@unpad.ac.id

Manuscript received: 22 January 2025. Revision accepted: 28 March 2025.

**Abstract.** Sule MIS, Fitriatin BN, Siswanto SY, Nurbaity A. 2025. *Unraveling key determinants of corn productivity: A correlation study of soil chemistry, biology, and climate in Sumedang, West Java, Indonesia. Asian J Agric 9: 201-207.* Corn productivity in areas with diverse agroecological conditions is influenced by several environmental factors such as soil chemistry, soil physics, soil biology, and climate conditions. The influence of these factors on corn productivity is significant and necessary to maintain or even increase corn plant productivity. This study aims to examine the conditions of soil chemistry, soil biology, and corn land climate and identify the correlation between environmental factors and corn yields, thereby determining the main factors of corn productivity in Sumedang, West Java, Indonesia. The study conducted using purposive sampling and an analytical approach at 18 observation locations, has practical implications for agricultural practices. By analysis was carried out by analyzing total phosphorus, cation exchange capacity, organic carbon, soil pH, phosphate-solubilizing bacteria, arbuscular mycorrhizal fungi, rainfall, temperature, and humidity; the study provides valuable insights for optimizing corn cultivation. The results of the correlation analysis show that each environmental factor has a different correlation strength with corn productivity. Soil chemistry factors have a weak-moderate correlation (0.26-0.43), soil biology is very weak (-0.36 to 0.02), and climate is weak-strong (-0.78 to 0.74). Environmental temperature conditions positively correlate ( $r = 0.74$ ) to corn productivity. This is likely due to increased soil mineralization processes, germination, and faster plant development at optimal temperatures. Conversely, environmental humidity negatively correlates ( $r = -0.78$ ) to corn productivity. This is likely because increased humidity can increase the risk of plant diseases (fungi), decrease photosynthesis efficiency, and limit soil aeration, thus affecting the health of corn plant roots. These findings underline the importance of maintaining the suitability of the corn cultivation environment amidst climate change, especially in tropical climates such as Indonesia.

**Keywords:** Agroecosystem, crop yield, microbial activity, soil fertility, sustainable agriculture

## INTRODUCTION

Corn (*Zea mays* L.) is one of the leading food crops, and its existence is essential in Indonesia and the world. Corn has broad uses, such as animal feed, humans, and industrial raw materials (de Matos Nascimento et al. 2020). The average per capita corn consumption per week in Indonesia in 2024 will reach 0.04 kg (BPS 2024a). Corn in Indonesia is important in maintaining food and economic security, especially in villages. This is because cultivating corn in the village is one of the livelihoods of local farmers and a source of their income. Corn production in Indonesia in 2024 was predicted to reach 15 million tons and experience an increase of 2.93% compared to production in 2023 (BPS 2024b). However, achieving sustainable productivity is influenced by complex interactions between land characteristics (soil chemistry and biology) and the environment (climate conditions).

Soil health in the form of soil chemical and biological properties is one of the main factors that can influence corn plant productivity. Soil chemical characteristics are related to the availability of nutrients in the soil for corn plants, such as total phosphorus (P), Cation Exchange Capacity

(CEC), organic Carbon (organic-C), and soil pH. P in the soil tends to be unavailable to plants because it is bound to aluminum (Al) and iron oxide (Fe), especially in acidic soils (Mabagala and Mng'ong'o 2022). Soil chemical properties can be influenced by cultivation practices carried out by farmers, such as the use of high doses of inorganic fertilizers. This condition causes competition between cations such as  $Mg^{2+}$  and  $Ca^{2+}$ , resulting in Mg deficiency in the soil. The ability of the soil to provide nutrients for plants is described by the CEC value (Yang et al. 2024). Apart from soil chemistry, factors that influence corn plants growth and productivity are the soil's biological conditions.

Soil biology in the form of soil microbiome structure and function affects soil fertility and plant health (Hartmann and Six 2023). Soil microbes play a role in decomposing organic matter, recycling nutrients, and increasing resistance to pathogens that cause plant diseases (Liu et al. 2022). The population and diversity of microbes such as Phosphate Solubilizing Bacteria (PSB) and soil Arbuscular Mycorrhizal Fungi (AMF) are the main factors that affect soil nutrient availability and plant productivity (Cavagnaro et al. 2015). AMF biomass is significantly positively correlated with

corn productivity cultivated using manure in the long term (Jiang et al. 2020). The relationship between the microbial population and corn plant productivity is still unclear. Several recent studies have reported an unclear relationship between microbial diversity and plant productivity, with positive (Lankau et al. 2022; Shu et al. 2022) and negative (Ali et al. 2020; Fan et al. 2021) correlations. In addition to soil conditions, chemical and biological soil environmental factors such as climate conditions are also significant factors influencing the success of corn cultivation.

Climate conditions also significantly affect corn plant growth. At crucial stages such as flowering and grain filling, extreme environmental temperatures can disrupt pollination, seed formation, and grain filling, ultimately reducing yields (Gourdji et al. 2013). Climate change is characterized by an increase in temperature and changes in rainfall patterns, thereby threatening the success of corn production throughout the world in the future (Ocwa et al. 2023). The research results by Zhang and Yang (2019) stated that increasing days of extreme temperatures in 2050 could reduce corn yields by 27.3%. Changes in rainfall can affect the effectiveness of soil moisture and nutrients (Zheng et al. 2024). Changes in rainfall affect plant photosynthesis and microbial activity by changing the availability of water and soil nutrients and directly affecting the carbon exchange process in the plant-soil system (Zhu et al. 2021).

Previous studies on increasing corn productivity in Indonesia have been widely conducted. However, most of them only focused on one factor affecting corn productivity separately (biological, chemical, or climatic conditions). The research results on the effect of interaction between soil properties and climatic conditions on corn productivity that have been carried out comprehensively are still limited. Given these conditions, this study aims to examine the chemical conditions of soil, soil biology, and the climate of corn fields, as well as to identify the correlation between corn yields and environmental factors so that the main factors of productivity can be determined. This study

was carried out in Sumedang, West Java, Indonesia, one of Indonesia's corn production centers.

## MATERIALS AND METHODS

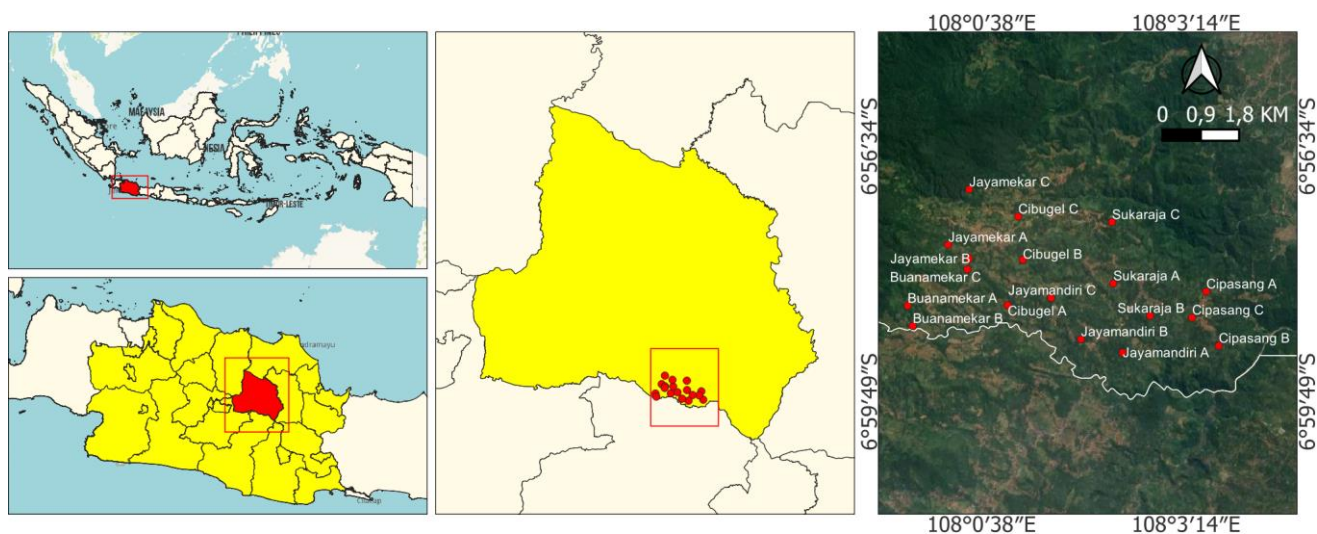
### Sampling location

The study was conducted from September 2022 to March 2023 using a purposive sampling method to determine the sampling location. It was conducted with an analytical approach at 18 observation location points (Figure 1) with the same land use type: land planted with NKSumo 7283 corn variety. The characteristics of land management at the sampling location are that land processing uses the minimum tillage method with fertilizer input in the form of 3.5-7 tons/ha of manure, 200-350 kg of NPK fertilizer, and 200-350 kg of Urea fertilizer. The sampling location was in Cibugel District, Sumedang, West Java, Indonesia, with an altitude of around 500-1,000 m above sea level and a 10-30% slope. Soil samples from each sampling location were analyzed at the Soil Biology Laboratory and the Soil Chemistry and Plant Nutrition Laboratory of Universitas Padjadjaran.

### Soil chemical analysis

#### *Nitrogen total (%)*

The nitrogen content analysis of the fertilizer was conducted using the Kjeldahl method, which involves several stages, including sample digestion, distillation, and titration (Gani et al. 2023). A completely homogenized sample of soil weighing precisely 250.0 mg was cautiously transferred into a Kjeldahl flask. Subsequently, 3 mL of H<sub>2</sub>SO<sub>4</sub> and 0.25-0.50 g of selenium were added to the mixture, which was shaken until completely homogenized. The mixture was then allowed to stand for 2 to 3 hours. The digestion was performed incrementally at temperatures between 150 and 350°C until a clear solution was obtained. After the solution was cooled, a small volume of distilled water was added to inhibit crystallization.



**Figure 1.** Soil sampling locations and characterization of corn cultivation in Sumedang, West Java, Indonesia

The distillate solution was poured into a boiling flask to a total volume of 250 mL, and deionized water was added until the flask reached the halfway mark. The distillate reservoir was set up in a 100 mL erlenmeyer flask, which contained 10 mL of 1% boric acid and three drops of Conway indicator. The distillation procedure involved the addition of 20 mL of 40% sodium hydroxide (NaOH). It was regarded as complete once the solution volume in the erlenmeyer flask reached 75. The resulting solution was then titrated with 0.05 N H<sub>2</sub>SO<sub>4</sub> until a transition from green to pink occurred. The volume of H<sub>2</sub>SO<sub>4</sub> used was measured, and the procedure was repeated to obtain the blank sample. The nitrogen content was calculated using the following formula:

$$\text{Nitrogen (\%)} = (V_c - V_b) \times N \times 14 \times f_k$$

Where: V<sub>c</sub> = Volume H<sub>2</sub>SO<sub>4</sub> titration (mL); V<sub>b</sub> = Volume H<sub>2</sub>SO<sub>4</sub> blank (mL); N = Normality of raw solution H<sub>2</sub>SO<sub>4</sub>; 14 = Atomic weight of nitrogen; 100 = % conversion; f<sub>k</sub> = Moisture content correction factor.

#### Organic carbon (%)

Analysis of soil C-organic content was carried out using the method used by Gani et al. (2023). A total of 50-100 mg of soil sample was put into a 100 mL measuring flask, and 5 mL of 2N K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> solution was added and then mixed until homogeneous. Furthermore, 7 mL of H<sub>2</sub>SO<sub>4</sub> was added to the solution and left for 30 minutes. The 250 ppm standard C solution was prepared using 5 mL of 5000 ppm standard C solution added to a 100 mL measuring flask. Then, 5 mL of H<sub>2</sub>SO<sub>4</sub> and 2N K<sub>2</sub>Cr<sub>2</sub>O<sub>7</sub> solution were added as in the 250 ppm standard C solution. Then, each solution was diluted to 100 mL and stirred until homogeneous. The absorbance value of each measurement was measured using a spectrophotometer with a wavelength of 651 nm. A standard curve was made to obtain a linear equation, which allows the determination of the x value of the solution. The C-organic content was calculated using the following formula.

$$\text{Organic-C (\%)} = \text{ppm curve} \times \text{mL} \times f_k$$

Where: Ppm curve = the sample rate was derived from the regression curve showing the relationship between the standard series rate and the reading, adjusted by subtracting the blank value; f<sub>k</sub> = moisture correction factor = 100 / (100 - % moisture content).

#### Phosphate analysis (%)

The total P content of the soil was described using spectrophotometry as conducted by Irwandhi et al. (2025). Five hundred mg of soil samples from each location were weighed and put into a digestion flask. Then, 0.5 mL of HClO<sub>4</sub> and 5 mL of HNO<sub>3</sub> were added and stirred until homogeneous. Furthermore, the mixture of materials was heated in a reactor with an initial temperature of 100°C. During the process, food produced yellow vapor in the tube. When the yellow vapor disappeared, the temperature was set to 200°C, and digestion was considered complete when white vapor appeared with a remaining liquid of about

0.5 mL. The solution was then shaken and diluted using deionized water to a volume of 50 mL, then filtered using W-41 filter paper to obtain extract A. One mL of extract A was mixed with 9 mL of deionized water in a 20 mL test tube and stirred until homogeneous. The solution then evolved to produce a 10-fold dilution (extract B). The absorbance value was measured using a spectrophotometer with a wavelength of 693 nm. A standard phosphate curve was then created to produce a linear equation used to calculate concentration (ppm).

#### pH analysis

Soil pH was measured using 10 g of dried and ground soil samples. The soil sample was placed in a beaker, and 25 mL of deionized water (1:2.5) was added. The soil and deionized water mixture was stirred until homogeneous using a magnetic stirrer and was left for 30 minutes. After that, the soil pH value was determined using a calibrated pH meter.

#### Soil biological analysis

Isolation of phosphate-solubilizing bacteria was carried out using a serial dilution method up to the 10<sup>-6</sup> level using Pikovskaya selective media (dextrose: 10 g L<sup>-1</sup>, Ca<sub>3</sub>(PO<sub>4</sub>)<sub>2</sub>: 5 g L<sup>-1</sup>, (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>: 0.5 g L<sup>-1</sup>, MgSO<sub>4</sub>.7H<sub>2</sub>O: 0.1 g L<sup>-1</sup>, yeast extract: 0.5 g L<sup>-1</sup>, FeSO<sub>4</sub>.7H<sub>2</sub>O: 0.0001 g L<sup>-1</sup>, KCl: 0.2 g L<sup>-1</sup>, MnSO<sub>4</sub>.7H<sub>2</sub>O: 0.0001 g L<sup>-1</sup>, Agar: 15 g L<sup>-1</sup>, pH 7). The cultures were then incubated at room temperature for 48 hours (Irwandhi et al. 2025).

#### Data analysis

Data analysis on each research variable was conducted using descriptive methods. Correlation analysis was conducted using Pearson correlation testing. Data visualization of the research findings was accomplished using Prism 9 software (Irwandhi et al. 2025).

## RESULTS AND DISCUSSION

### Chemical properties of corn cultivation

Soil chemical properties at a depth of 0-30 cm are analyzed, including total P, Cation Exchange Capacity (CEC), organic Carbon (C-organic), and soil pH (Figure 2). The figure shows that each research location point has different soil chemical properties. The total P content ranges from 6.26-17.39%, with location K showing the highest total P concentration at 17.39% (Figure 2.A). High total P content (location K) can increase the availability of P for maize plants. Phosphorus is an essential nutrient for plants, especially for root formation, plant growth, and seed formation (Malhotra et al. 2018). Sufficient P availability will support increasing maize productivity (Ademba et al. 2015).

The CEC value ranges from 9.01-16.40 cmol kg<sup>-1</sup> (Figure 2.B), with the highest CEC value at location R (Jayamandiri 3), 16.40 cmol kg<sup>-1</sup>. The soil CEC value is one of the important factors that can affect the availability of nutrients for plants. High CEC allows the soil to retain more cations so that the soil becomes rich in calcium

(Ca<sup>2+</sup>), sodium (Na<sup>+</sup>), magnesium (Mg<sup>2+</sup>), and other cations. Previous studies have shown that increasing CEC affects the increase in chlorophyll content, nitrogen absorption, and plant biomass (Yang et al. 2024).

Organic-C levels vary around 1.12 to 2.27% at each location (Figure 2.C), with the highest organic-C content at location H (Cibugel 2), which is 2.27%. Soil organic-C content can indicate soil quality conditions such as soil structure, nutrient cycles, and soil biota (Hoffland et al. 2020). High organic-C can be used as an energy source for microorganisms in the soil (Creamer et al. 2022). Soil pH at each location has almost the same conditions (Figure 2.D), around 5.05-5.58, with location C (Cipasang 3) having the highest pH (5.58). Soil that is too acidic or alkaline can harm soil physical properties and reduce nutrient availability (Xia et al. 2024).

### Biological properties of corn cultivation

Soil biology analysis showed that each location had soil biology conditions, such as Phosphate Solubilizing Bacteria

(PSB) and Arbuscular Mycorrhizal Fungi (AMF) with different populations (Figure 3). These microbes play a role in providing P nutrients for corn plants. The PSB population at each location varied from 1.05 to 21.00 × 10<sup>6</sup> CFU g<sup>-1</sup>, with location I (Cibugel 3) having the highest PSB population, 21.00 × 10<sup>6</sup> CFU g<sup>-1</sup>. The AMF population varied from 130-426 spores g<sup>-1</sup>, with location O (Buanamekar 3) having the highest AMF population (426 spores g<sup>-1</sup>). A high AMF population in corn cultivation land will increase P availability by up to 102.90% for corn plants (Kazadi et al. 2021). PSB can increase P availability for plants by changing bound P, while AMF can increase plant P absorption through root tissue (Billah et al. 2019). A high population of phosphate-solubilizing microbes can increase the efficiency of P fertilization (Elhassoufi et al. 2021). In addition, phosphate-solubilizing microbes can also produce phytohormones such as Indole-3-Acetic Acid (IAA), cytokinins, and gibberellins, which can be used to support plant growth (Sodiq et al. 2019).

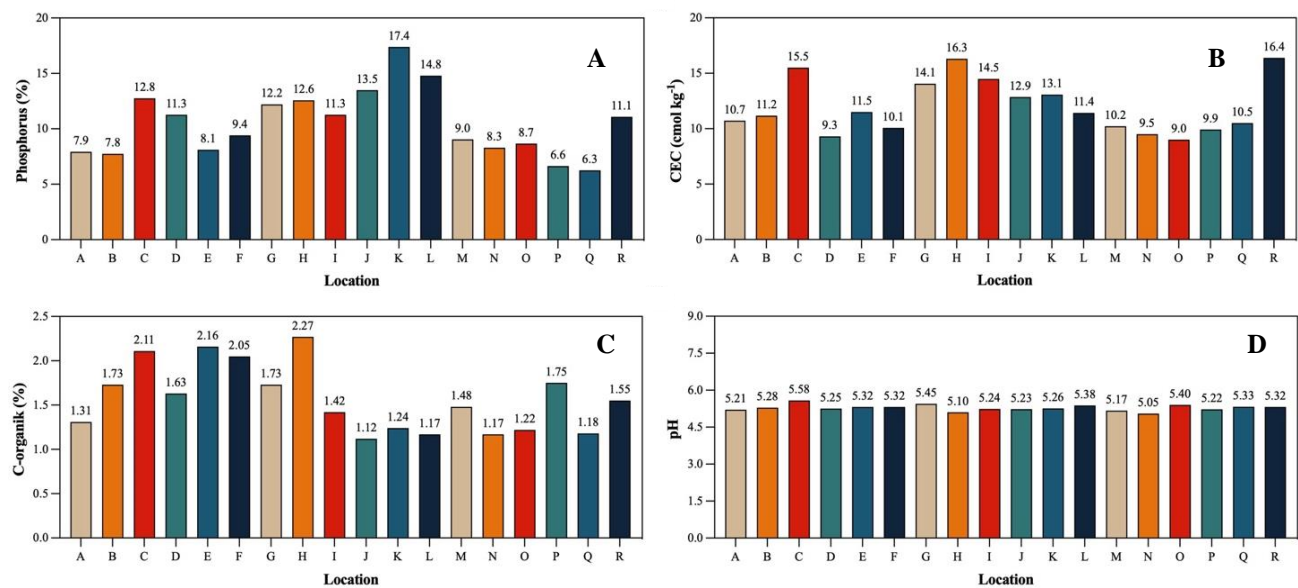


Figure 2. Soil chemical conditions at corn cultivation locations. A. Phosphorus; B. Cation exchange capacity; C. Organic carbon; D. pH

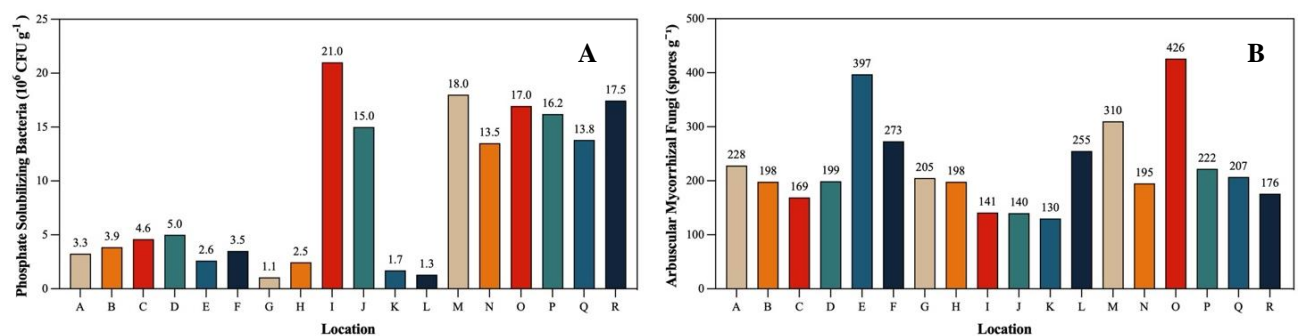


Figure 3. Soil biological conditions at corn cultivation locations. A. Phosphate solubilizing bacteria; B. Arbuscular mycorrhizal fungi

**Climate condition of corn cultivation**

Average climate conditions such as rainfall, temperature, and humidity during corn cultivation can be observed in Figure 4. The average rainfall (Figure 4.A) was around 315 to 380 mm annually, with the highest rainfall at location F (Sukaraja 3). The appropriate rainfall to support optimal corn growth was around 300-500 mm during cultivation activities (Wang et al. 2020). The average temperature (Figure 4.B) and humidity (Figure 4.C) at each location were around 22.4-23.7°C and 78.5-80.2%. These conditions are still suitable for corn plant growth because the optimal temperature is around 20.0-30.0°C (Beegum et al. 2023). Climatic conditions will also indirectly impact soil microorganisms, so they can affect biogeochemical processes that affect the availability of nutrients and plant pathogens (Ughamba et al. 2025).

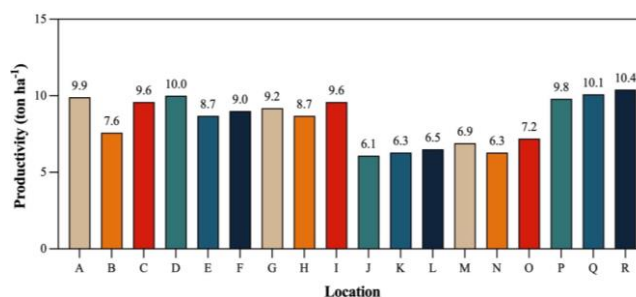
**Corn productivity**

The results of the corn productivity analysis (Figure 5) show a variation in yield among locations of around 6.1 to 10.4 tons ha<sup>-1</sup>. The locations with the highest productivity were R (Jayamandiri 3), Q (Jayamandiri 2), and D (Sukaraja 1), with productivity of 10.4, 10.1, and 10.0 tons ha<sup>-1</sup>, respectively. This condition has a fairly high difference, around 63.9-70.9% higher compared to location J (Jayamekar 1), with a productivity of 6.1 tons ha<sup>-1</sup>.

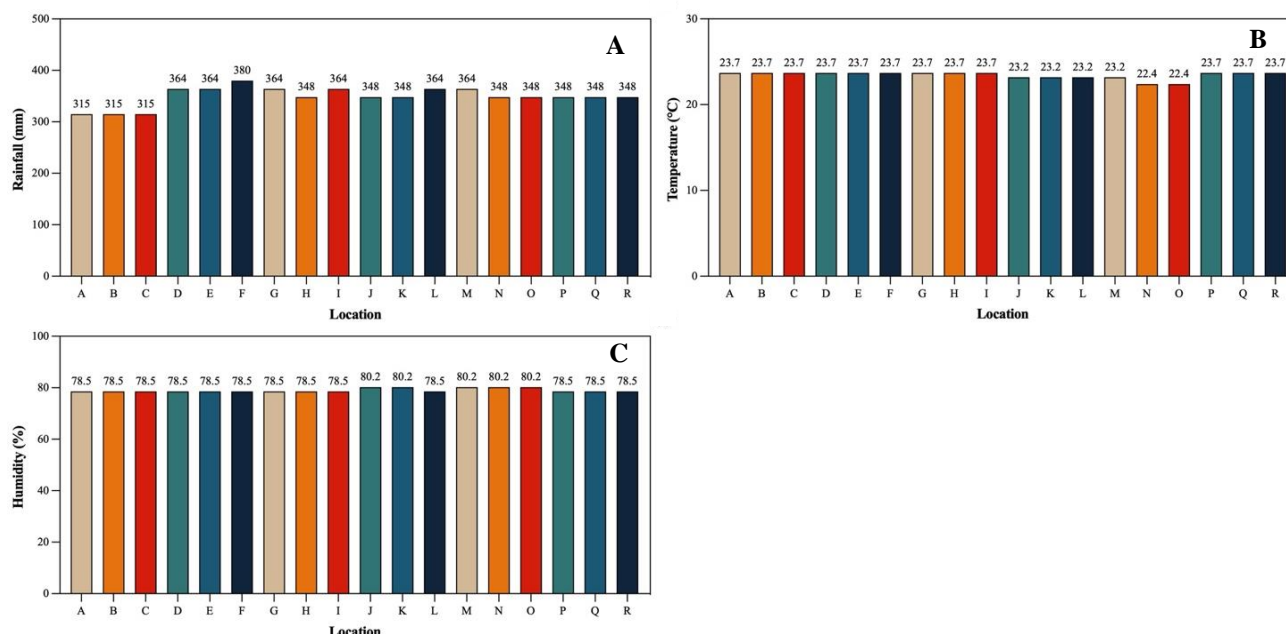
**Pearson's correlation analysis of growth traits in maize**

Correlation analysis was conducted to assess the relationship between various environmental factors on corn plant productivity in the forms of phosphate solubilizing bacteria (PSB), arbuscular mycorrhizal fungi (AMF), total

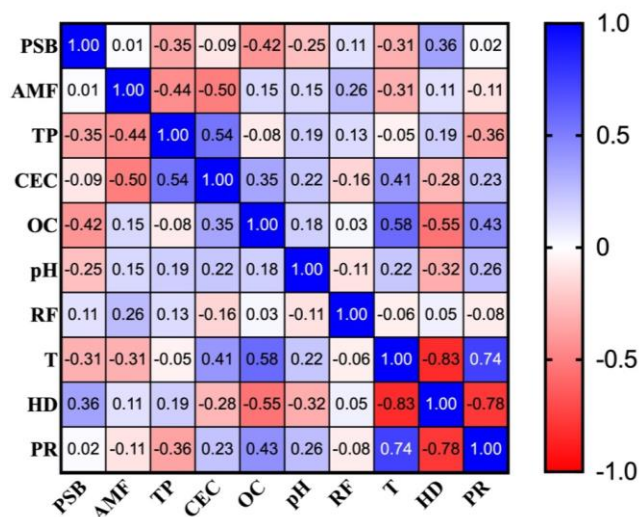
phosphate (TP), cation exchange capacity (CEC), organic carbon (OC), pH (pH), rainfall (RF), temperature (T), and humidity (HD). The results of the Pearson correlation analysis in Figure 5 indicate that each corn productivity has a different level of relationship with environmental factors. The strength of the correlation between variables can be assessed using the absolute value of r, very strong (0.90-1.00), strong (0.70-0.89), moderate (0.40-0.69), weak (0.10-0.39), and negligible (0.00-0.10) (Pengphorm et al. 2024). The results of the correlation analysis showed that biotic factors in the forms of PSB and AMF each had a very weak or negligible correlation (0.02 and -0.11) on corn productivity. This may be due to the influence of soil chemical properties such as pH and limited availability of organic matter. This aligns with previous research that AMF colonization is influenced by soil and climate conditions (Li et al. 2025).



**Figure 5.** Corn productivity in corn cultivation in Sumedang, West Java, Indonesia



**Figure 4.** Climate conditions at corn cultivation locations. A. Rainfall; B. Temperature; C. Humidity



**Figure 6.** The correlation between maize productivity and biotic-abiotic environmental factors was analyzed. The environmental factors considered include Phosphate Solubilizing Bacteria (PSB), Arbuscular Mycorrhizal Fungi (AMF), Total Phosphate (TP), Cation Exchange Capacity (CEC), Organic Carbon (OC), pH (pH), Rainfall (RF), Temperature (T), Humidity (HD), and Productivity (PR)

Figure 6 shows that soil chemical factors such as TP, CEC, organic-C, and pH have weak to moderate correlations with  $r$  values of -0.36, 0.23, 0.43, and 0.26, respectively. The weak negative correlation between TP and productivity indicates that high TP content is not always directly proportional to the P that plants can absorb. In acidic soils, P is not available to plants because  $Al^{2+}$  and  $Fe^{2+}$  bind it, so plants cannot absorb it (Basílio et al. 2022). Corn productivity has a very low correlation with rainfall (-0.08), indicating that rainfall does not significantly impact productivity. Climatic factors such as temperature have a strong positive correlation (0.74), while humidity has a strong negative correlation. This shows that higher environmental temperatures within the optimal range can increase productivity, while high environmental humidity can decrease productivity. In environments with high humidity, it can increase the presence of plant pests and diseases and inhibit nutrient absorption.

In conclusion, soil chemical factors such as TP, CEC, organic-C, pH, PSB, and AMF analysis at each location had different conditions, with the highest results at respective locations K (17.39%), R (16.40  $cmol\ kg^{-1}$ ), H (2.27%), C (5.58), I ( $21 \times 10^6\ CFU\ g^{-1}$ ), and O (426 spores  $g^{-1}$ ). The average rainfall, temperature, and humidity conditions at each location were respectively around 315-380 mm, 22.4-23.7°C, and 78.5-80.2%. The results of the correlation analysis show that each environmental factor has a different correlation strength with corn productivity. Soil chemistry factors have a weak-moderate correlation (0.26-0.43), soil biology is very weak (-0.36 to 0.02), and climate is weak-strong (-0.78 to 0.74). Temperature conditions have a positive correlation with a value of 0.74, while humidity has a negative correlation of -0.78 on corn plant productivity. Climate factors (temperature and humidity) are determining factors and greatly influence the success of corn cultivation.

## ACKNOWLEDGEMENTS

The author would like to express his appreciation to the Universitas Padjadjaran Academic Leadership Grant (ALG) for their valuable support and funding of the research and publication of this article.

## REFERENCES

- Ademba JS, Kwach JK, Esilaba AO, Ngari SM. 2015. The effects of phosphate fertilizers and manure on maize yields in South Western Kenya. *East Afr Agric For J* 81 (1): 1-11. DOI: 10.1080/00128325.2015.1040640.
- Ali S, Saldias S, Weerasuriya N, Delaney K, Kandasamy S, Lazarovits G. 2020. Corn microbial diversity and its relationship to yield. *Can J Microbiol* 66 (8): 457-473. DOI: 10.1139/cjm-2020-0002.
- Basílio F, Dias T, Santana MM, Melo J, Carvalho L, Correia P, Cruz C. 2022. Multiple modes of action are needed to unlock soil phosphorus fractions unavailable for plants: The example of bacteria-and fungi-based biofertilizers. *Appl Soil Ecol* 178: 104550. DOI: 10.1016/j.apsoil.2022.104550.
- Beegum S, Walne CH, Reddy KN, Reddy V, Reddy KR. 2023. Examining the corn seedling emergence-temperature relationship for recent hybrids: Insights from experimental studies. *Plants* 12 (21): 3699. DOI: 10.3390/plants12213699.
- Billah M, Khan M, Bano A, Hassan TU, Munir A, Gurmani AR. 2019. Phosphorus and phosphate solubilizing bacteria: Keys for sustainable agriculture. *Geomicrobiol J* 36 (10): 904-916. DOI: 10.1080/01490451.2019.1654043.
- BPS. 2024a. Average weekly per capita consumption of key food items, 2007-2024. <https://www.bps.go.id/id/statistics-table/1/OTUwIzE=/rata-rata-konsumsi-per-kapita-seminggu-beberapa-macam-bahan-makanan-penting--2007-2023.html>. [Indonesian]
- BPS. 2024b. Maize harvest area and production in Indonesia 2024. <https://www.bps.go.id/id/pressrelease/2024/10/15/2378/pada-2024--luas-panen-jagung-pipilan-diperkirakan-sebesar-2-58-juta-hektare-dan-produksi-jagung-pipilan-kering-dengan-kadar-air-14-persen-sebesar-15-21-juta-ton-.html>. [Indonesian]
- Cavagnaro TR, Bender SF, Asghari HR, Heijden MGAV. 2015. The role of arbuscular mycorrhizas in reducing soil nutrient loss. *Trends Plant Sci* 20 (5): 283-290. DOI: 10.1016/j.tplants.2015.03.004.
- Creamer RE, Barel JM, Bongiorno G, Zwetsloot MJ. 2022. The life of soils: Integrating the who and how of multifunctionality. *Soil Biol Biochem* 166: 108561. DOI: 10.1016/j.soilbio.2022.108561.
- de Matos Nascimento A, Maciel AM, Silva JBG, Mendonça HV, de Paula VR, Otenio MH. 2020. Biofertilizer application on corn (*Zea mays*) increases the productivity and quality of the crop without causing environmental damage. *Water Air Soil Pollut* 231: 414. DOI: 10.1007/s11270-020-04778-6.
- Elhaissoufi W, Ghoulam C, Barakat A, Zeroual Y, Bargaz A. 2021. Phosphate bacterial solubilization: A key rhizosphere driving force enabling higher P use efficiency and crop productivity. *J Adv Res* 38: 13-28. DOI: 10.1016/j.jare.2021.08.014.
- Fan K, Delgado-Baquerizo M, Guo X, Wang D, Zhu YG, Chu H. 2021. Biodiversity of key-stone phylotypes determines crop production in a 4-decade fertilization experiment. *ISME J* 15 (2): 550-561. DOI: 10.1038/s41396-020-00796-8.
- Gani A, Jannah DM, Zulfadli Z. 2023. Macronutrient analysis of organic fertilizer from the mixture of *Casuarina equisetifolia* leaf litter and *Ananas comosus* rind waste with effective microorganism bioactivator. *Jurnal Pena Sains* 10 (1): 11-19. DOI: 10.21107/jps.v10i1.17432.
- Gourdji SM, Sibley AM, Lobell DB. 2013. Global crop exposure to critical high temperatures in the reproductive period: Historical trends and future projections. *Environ Res Lett* 8: 024041. DOI: 10.1088/1748-9326/8/2/024041.
- Hartmann M, Six J. 2023. Soil structure and microbiome functions in agroecosystems. *Nat Rev Earth Environ* 4 (1): 4-18. DOI: 10.1038/s43017-022-00366-w.
- Hoffland E, Kuyper TW, Comans RN, Creamer RE. 2020. Eco-functionality of organic matter in soils. *Plant Soil* 455: 1-22. DOI: 10.1007/s11104-020-04651-9.

- Irwandhi, Kamaluddin NN, Khumairah FH, Prihatiningsih N, Simarmata T. 2025. Assessment of local wisdom biofertilizer formulas on enhancing microbial diversity and photosynthate allocation in acid-stressed maize. *Asian J Agric* 9 (1): 112-121. DOI: 10.13057/asianjagric/g090112.
- Jiang Y, Luan L, Hu K, Liu M, Chen Z, Geisen S, Chen X, Li H, Xu Q, Bonkowski M, Sun B. 2020. Trophic interactions as determinants of the arbuscular mycorrhizal fungal community with cascading plant-promoting consequences. *Microbiome* 8: 142. DOI: 10.1186/s40168-020-00918-6.
- Kazadi AT, Lwalaba wa Lwalaba J, Ansey BK, Muzulukwau JM, Katabe GM, Karul MI, Baert G, Haesaert G, Mundende RPM. 2022. Effect of phosphorus and Arbuscular Mycorrhizal Fungi (AMF) inoculation on growth and productivity of maize (*Zea mays* L.) in a tropical ferralsol. *Gesunde Pflanzen* 74: 159-165. DOI: 10.1007/s10343-021-00598-8.
- Lankau RA, George I, Miao M. 2022. Crop performance is predicted by soil microbial diversity across phylogenetic scales. *Ecosphere* 13 (5): e4029. DOI: 10.1002/ecs2.4029.
- Liu H, Du X, Li Y, Han X, Li B, Zhang X, Li Q, Liang W. 2022. Organic substitutions improve soil quality and maize yield through increasing soil microbial diversity. *J Clean Prod* 347: 131323. DOI: 10.1016/j.jclepro.2022.131323.
- Mabagala FS, Mng'ong'o ME. 2022. On the tropical soils; The influence of organic matter (OM) on phosphate bioavailability. *Saudi J Biol Sci* 29 (5): 3635-3641. DOI: 10.1016/j.sjbs.2022.02.056.
- Malhotra H, Vandana, Sharma S, Pandey R. 2018. Phosphorus Nutrition: Plant Growth in Response to Deficiency and Excess. In: Hasanuzzaman M, Fujita M, Oku H, Nahar K, Hawrylak-Nowak B (eds.). *Plant Nutrients and Abiotic Stress Tolerance*. Springer, Singapore. DOI: 10.1007/978-981-10-9044-8\_7.
- Ocwa A, Harsanyi E, Széles A, Holb IJ, Szabó S, Rátonyi T, Mohammed S. 2023. A bibliographic review of climate change and fertilization as the main drivers of maize yield: implications for food security. *Agric Food Secur* 12(1): 1-18. DOI: 10.1186/s40066-023-00419-3.
- Pengphorm P, Thongrom S, Daengngam C, Duangpan S, Hussain T, Boonrat P. 2024. Optimal-band analysis for chlorophyll quantification in rice leaves using a custom hyperspectral imaging system. *Plants (Basel)* 13 (2): 259. DOI: 10.3390/plants13020259.
- Shu X, He J, Zhou Z, Xia L, Hu Y, Zhang Y, Zhang Y, Luo Y, Chu H, Liu W, Yuan S, Gao X, Wang C. 2022. Organic amendments enhance soil microbial diversity, microbial functionality and crop yields: A meta-analysis. *Sci Total Environ* 829: 154627. DOI: 10.1016/j.scitotenv.2022.154627.
- Sodiq AH, Setiawati MR, Santosa DA, Widayat D. 2019. The potency of bio-organic fertilizer containing local microorganism of Cibodas Village, Lembang-West Java. *IOP Conf Ser: Earth Environ Sci* 383: 012001. DOI: 10.1088/1755-1315/383/1/012001.
- Ughamba KT, Ndukwe JK, Lidbury IDEA, Nnaji ND, Eze CN, Aduba CC, Groenhof S, Chukwu KO, Anyanwu CU, Nwaiwu O, Anumudu CK. 2025. Trends in the application of phosphate-solubilizing microbes as biofertilizers: Implications for soil improvement. *Soil Syst* 9 (1): 6. DOI: 10.3390/soilsystems9010006.
- Wang P, Wu D, Yang J, Ma Y, Feng R, Huo Z. 2020. Summer maize growth under different precipitation years in the Huang-Huai-Hai Plain of China. *Agric For Meteorol* 285-286: 107927. DOI: 10.1016/j.agrformet.2020.107927.
- Xia Y, Feng J, Zhang H, Xiong D, Kong L, Seviour R, Kong Y. 2024. Effects of soil pH on the growth, soil nutrient composition, and rhizosphere microbiome of *Ageratina adenophora*. *PeerJ* 12: e17231. DOI: 10.7717/peerj.17231.
- Yang M, Zhou D, Hang H, Chen S, Liu H, Su J, Lv H, Jia H, Zhao G. 2024. Effects of balancing exchangeable cations Ca, Mg, and K on the growth of tomato seedlings (*Solanum lycopersicum* L.) based on increased soil cation exchange capacity. *Agronomy* 14 (3): 629. DOI: 10.3390/agronomy14030629.
- Zhang Q, Yang Z. 2019. Impact of extreme heat on corn yield in main summer corn cultivating area of China at present and under future climate change. *Intl J Plant Prod* 13: 267-274. DOI: 10.1007/s42106-019-00052-w.
- Zheng S, Cha X, Dong Q, Guo H, Sun L, Zhao Q, Gong Y. 2024. Effects of rainfall patterns in dry and rainy seasons on the biomass, ecostochiometric characteristics, and NSC content of *Fraxinus malacophylla* seedlings. *Front Plant Sci* 15: 1344717. DOI: 10.3389/fpls.2024.1344717.
- Zhu W, Xu Y, Yu H, Wang P, Huang J. 2021. Effects of precipitation and nitrogen addition on ecosystem carbon exchange in a desert steppe in Ningxia. *Acta Ecol Sin* 41 (16): 6679. DOI: 10.5846/stxb202009092351.